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Tradespace Exploration for the Engineering of Resilient Systems

by Eric Spero, Michael Avera, Pierre Valdez, and Simon Goerger

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14. ABSTRACT

Tradespace exploration (TSE) supports the systems engineering technical management process of decision analysis by identifying compromises, revealing opportunities, and communicating the impacts of decisions across a system's development life cycle. TSE for Engineered Resilient Systems is envisioned to coalesce pertinent information tuned to specific decision makers, at the appropriate time, presenting a holistic view of decision impacts on required system capabilities. A "best common practice" process for establishing, managing, and exploring tradespaces is assembled. Several TSE tools are assessed against process steps and tool attributes. This study reveals that having a valid set of attributes and an understanding of how a cross section of tools can satisfy them is insufficient—what is needed is a deeper understanding of how these tools are used and, more importantly, how they can be used when performing TSE in support of the decision analysis process. Gaining this understanding will enable users to better assess if they possess the appropriate tradespace exploration tools.

15. SUBJECT TERMS

tradespace exploration, decision analysis, ERS, trade-off analysis, trade study process

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1. Introduction

As the Department of Defense (DOD) moves toward addressing geopolitical environments marked by rapidly changing threats, tactics, mission scenarios, technologies, and available funding, advanced methods, processes, and tools are needed to effectively engineer resilient system solutions. The resulting resilient systems must be adaptable to a wider range of mission contexts, across multiple alternative futures. To support resilient system design, and a correspondingly resilient design process, tradespace exploration (TSE) provides decision makers an understanding of capabilities, gaps, and potential compromises facilitating the achievement of system metric objectives. The decisions being made throughout a system's development life cycle are continuously redefining its capabilities, performance, cost, manufacturability, delivery schedule, and sustainability. To be effective, decision makers must have deep knowledge of the component elements of a system, including how these elements interact internally to the system and externally with the operational environment. TSE provides decision makers an understanding of candidate system component choices and the implications on multiple missions across joint Warfighting environments.[1]

Throughout a system's development life cycle, and across its hierarchy, trades are being performed with multiple types and quantities of data coming out of varying levels of analysis fidelity. From a system's functional perspective, capabilities (e.g., lighter weight, higher performing) map to system measures of performance, which in turn map to measures of effectiveness, which ultimately affect operational figures of merit that determine how well a system, or a portfolio of systems, meets a required capability. Concurrently, there is a product hierarchy within which various technologies can be applied, from the component level, and up to subsystem, system, and finally a portfolio of heterogeneous systems working concurrently to fulfill a role. Additionally, there are process considerations such as industrial base, training, policy, and procedures, which are often omitted from the decision analysis process for various reasons. Although the decisions being made throughout these functional, product, and process perspectives differ, decision makers at the highest levels will execute based on the relationship between the benefit achieved by, and the life cycle cost (LCC) associated with, a particular asset mix. Therefore, if the tradeoff between benefit and cost can be generated, explored, and then presented in the context of the holistic system, a more informed decision can be made across the system perspectives.

To aid the decision maker in performing effective TSE under these complex circumstances, the Engineered Resilient Systems (ERS) effort involves providing the necessary engineering concepts, methods, processes, and tools.[2] The goals of ERS are to provide to engineering, Warfighting, and acquisition decision makers the needed capability to manage TSE activities with full and consistent information throughout the life of the systems by the following[2]:

- Producing more complete and robust requirements pre-Milestone A
- Making the engineering design process much more efficient and effective
- Considering the manufacturability of a proposed design explicitly
- Establishing baseline resiliency of current capabilities

The TSE methods, processes, and tools should enable deeper consideration of system design alternatives while keeping the space as open as possible to address resiliency and robustness to changing conditions and constraints.

The tradespace frontier of Fig. 1[3] depicts that information coming out of knowledge databases must support decision making across the life cycle by communicating to multiple perspectives and across the system hierarchy, while taking into account fiscal and environmental constraints. What this means is that TSE tools and processes are needed at different levels of the product hierarchy, commensurate with the decisions being made, the information available to make decisions, and the person or organization making decisions.

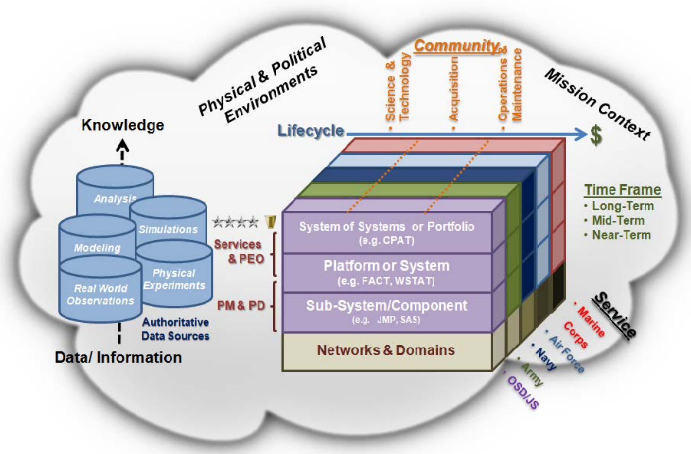

Fig. 1 ERS tradespace frontier

2. Assumptions

- TSE is performed throughout a system's life cycle, in support of decision making, in a step-by-step process.
- There exist organization-specific best practice methods, processes, and tools for performing TSE.
- TSE is often performed to justify selection of a reduced set of options from a broader set of alternatives, rather than for understanding how compromises in system design can increase value delivered to stakeholders.
- TSE is largely performed ad hoc, and with the tools on-hand, without investigation into how other tools can be brought in to fill gaps in a TSE process.
- TSE is performed to "make better decisions", but without criteria for measuring the effectiveness, efficiency, correctness, or consistency of decisions across the life cycle.

3. Approach

The approach to reveal whether TSE best practices are on a trajectory to meet the needs of ERS involves the following: 1) sources of TSE methods, processes, and tools were identified, 2) common approaches in TSE were documented, 3) a set of TSE tool requirements was developed, 4) the most commonly used TSE tools, as well as other tools that could be implemented in a formal TSE process, were identified, and 5) an evaluation was performed.

When making a decision, in this case regarding the tools to use in exploring a tradespace, a common approach is to start with alternatives and determine which alternative best meets the decision maker's intent. A preferred approach is one based on value-focused thinking (VFT), where value-producing objectives are developed, alternatives are identified, and decisions are made based on how much value the alternatives provide across the objectives.[4] Applied formally, a VFT approach involves interviews with decision makers to help translate the perceived increase in an evaluation metric into a value curve. In this study, a modified VFT approach was started; a recommendation will be made for expanding the current approach to

include generating value curves and assigning swing weights to value measures for application to an additive value model.

To initiate a VFT approach, a fundamental objective was developed assuming that TSE is a process that uses tools to arrive at decisions:

Use a tradespace tool, or set of tools, to make actionable decisions across the system hierarchy and throughout the system life cycle.

To evaluate a tool's performance within a TSE process, several pieces of information were needed: TSE tools, TSE process steps, attributes that define TSE tools, and attributes that define what users are doing with their TSE tools.

4. Tradespace Analysis Tool Requirements Identification

An audit was performed to identify the existing TSE tools used by the ERS Demonstration Projects (DPs),[1] as well as elsewhere in the services and industry, throughout a system's life cycle. A set of attributes that define various TSE tools was developed, and the tools were mapped to the attributes to aid in identifying existing tools that are closely aligned with needed capabilities.

4.1 TSE Tools

The following sources were used to identify TSE tools:

- Operations Research/Management Sciences (OR/MS) Today Decision Analysis Software (DAS) Survey[5,6]
- Rexer Analytics Data Miner Survey[7]
- ERS DPs[8–10]
- ERS Priority Steering Council (PSC) Tools Assessment[11]
- US Army Research Laboratory (ARL) internal organization research and experience

After completing the audit of tools, it was apparent that what most refer to as a decision analysis or data mining tool could be misconstrued as a satisfactory ERS TSE tool. To better understand how a decision analysis tool is viewed, a definition

of decision analysis developed by Buede,[12] and referred to in the 2010 OR/MS Today survey summary,[5] is provided:

"Decision analysis is the discipline of evaluating complex alternatives in the light of uncertainty, value preferences and risk preference."

Although the process of decision analysis, as described in the Defense Acquisition University's Defense Acquisition Guidebook,[13] is not TSE in and of itself, it is supported by TSE. In the case of data mining tools, the corresponding Data Miner Survey[7] does not provide a formal definition, but similarities to TSE activities are apparent with terms such as regression, models, and data visualization.

The ERS PSC assessment[11] was filtered for tools in the "Data Driven Tradespace Exploration and Analysis" section. In addition to the source materials in Section 4.1, the ERS DP leads provided overview presentations and were informally interviewed via telephone. These sources all revealed that there are many tools in use across academia, government, and industry for performing TSE. In all, 81 tools were identified, shown in Table 1 (the authors recognize that more tools exist than are captured here). A short description of each tool is provided in Appendix A.

Table 1 TSE tools and developers

Tool/Process	Developer	Tool/Process	Developer
@RISK	Palisade Corporation	Mathematica	Wolfram
AAMODAT	ARDEC	MedModel Suite	ProModel Corporation
AgenaRisk	Agena Limited	modeFRONTIER	Esteco
Analytica	Lumina Decision Systems	ModelCenter	Phoenix Integration
Analytics	SAS	Nexus	iChrome Ltd.
ASEC	TARDEC	OpenMDAO	NASA
ATSV	PSU-ARL	OptiY	OptiY GmbH
Berkeley Madonna	University of California at Berkeley	Portfolio Simulator	ProModel Corporation
CART	Salford Systems	Process Simulator	ProModel Corporation
ClearPoint Strategy	Ascendant Strategy Management Group	Project Simulator	ProModel Corporation
Comparion Suite	Expert Choice, Inc.	Promax Professional	Cogentus Consulting Ltd
CPAT	PEO-GCS	ProModel Suite	ProModel Corporation
CyDesign Studio	CyDesign Labs	R	R Foundation
D3	D3JS.org	RandomForests	Salford Systems
DAKOTA	Sandia National Labs	Rave	Georgia Tech
DEA SolverPro	SAITECH, Inc.	RICH Decisions	SAL, Aalto University
DecideIT	Preference	Risk Solver Pro	Frontline Systems, Inc.
Decision Explorer	Banxia Software Ltd	RiskSim	TreePlan Software

Table 1 TSE tools and developers (continued)

Tool/Process	Developer	Tool/Process	Developer
DecisionTools Suite 6.0	Palisade Corporation	ROSETTA	ASDL, Georgia Tech
D-Sight Desktop	D-Sight	RPM Decisions	SAL, Aalto University
Enterprise Portfolio Simulator	ProModel Corporation	SAE	MITRE
Equity3	Catalyze Ltd	Salford Predictive Modeler	Salford Systems
Eureqa Desktop	Nutonian, Inc.	SCAP	SLAD
Excel	Microsoft	SensIt	TreePlan Software
ExtendSim Suite	Imagine That, Inc.	ServiceModel	ProModel Corporation
FACT	GTRI	SIMULIA	Dassault Systèmes
ForeTell-DSS	DecisionPath, Inc.	Smart-Swaps	SAL, Aalto University
GoldSim	GoldSim Technology Group	SPIDR	University of Southern California
gPROMS	Process Systems Enterprise Limited	STATISTICA	StatSoft
GRIPS	The Aerospace Corp	Tableau	tableau software
Hiview3	Catalyze Ltd	TIES	ASDL, Georgia Tech
Iris	Ayasdi	TRACER	LMI
Isight	Dassault Systèmes	TreeNet	Salford Systems
JIAT	ODASA-CE	TreePlan	TreePlan Software
JMP	SAS	TreePlan Toolkit	TreePlan Software
KNITRO	Ziena Optimization LLC	VisLab	MIT
Logical Decisions for Windows	Logical Decisions	VisualDOC	Vanderplaats R&D, Inc.
Logical Decisions Portfolio	Logical Decisions	Web-HIPRE	SAL, Aalto University
MapleSim	Maplesoft	WSTAT	PEO-GCS
MARS	Salford Systems		

Notes: AAMODAT = Armament Analysis Multiple Objectives Decision Analysis Tool; ARDEC = US Army Research, Development and Engineering Center; ASDL = Aerospace Systems Design Laboratory; ASEC = Advanced Systems Engineering Capability; ATSV = ARL Trade Spaec Visualizer; CART = Classification and Regression Trees; CPAT = Capability Portfolio Analysis Tool; DAKOTA = Design Analysis toolKit for Optimization and Terascale Applications; FACT = Framework for Assessing Cost and Technology; GRIPS = Genetic Resources for Innovation and Problem Solving; GTRI = Georgia Tech Research Institute; JIAT = Joint Integrated Analysis Tool; LMI = Logistics Management Institute; MARS = Multivariate Adaptive Regression Splines; MIT = Massachusetts Institute of Technology; NASA = National Aeronautics and Space Administration; ODASA-CE = Office of the Deputy Assistant Secretary of the Army for Cost and Economics; PEO-GCS = Program Executive Office Ground Combat Systems; PSU-ARL = Pennsylvania State University Applied Research Laboratory; RICH = Rank Inclusion in Criteria Hierarchies; ROSETTA = Relational-Oriented Systems Engineering and Technology Tradeoff Analysis; RPM = Robust Portfolio Management; SAE = Systems Analysis and Experimentation; SAL = Systems Analysis Laboratory; SCAP = System Capabilities Analytic Process; SLAD = Survivability/Lethality Analysis Directorate; SPIDR = Systems Platform for Integrated Design in Realtime; TARDEC = US Army Tank Automotive Research, Development and Engineering Center; TIES = Technology Identification, Evaluation, and Selection; TRACER = Tradespace Analysis for Capabilities, Effectiveness, and Resources; WSTAT = Whole System Trades Analysis Tool

4.2 TSE Tool Reduction

After identifying a large number of tools for initial consideration, the next step was to reduce the set to a manageable size, knowing that the subsequent tasks would involve identifying attributes and then mapping tools to those attributes in an attribute-by-tool sized matrix. A set of keep-or-reject criteria was developed. The first criterion was a gate: if the tool was in use by any of the ERS DP teams, then it was kept for consideration in the present study, and if not, then it entered into a set of filter criteria. The first filter criterion was whether the tool or developer was still available; in several cases an Internet search for the tool or developer returned limited results or no web page. The next filter criterion was whether the tool was included as part of a larger suite of tools; in several cases individual tools were rolled into a larger suite by the developer, in which case the suite was assessed for evaluation as opposed to the individual tools. The final filter criterion was if the tool was specific to a domain outside of system design and analysis (e.g., medical or service industry); tools with a niche function were omitted to focus on tools that encompassed a broad TSE process. This initial filtering reduced the tool set by 38.

The remaining 43 tools were reassessed to determine if they should be evaluated in the current effort or deferred to a follow-on effort. The first filter criterion at this level was if the tool's development or use was supported by any known DOD TSE effort, or if it was presently receiving DOD funding for continued development and application; if so, then it was kept for current consideration. The next filter criterion was if the tool received high ranking and/or positive feedback from other tool surveys; several tools showed consistent or rising popularity, which the authors assessed as indicative of high user satisfaction. The final filter criterion was if the authors had any familiarity with the tool whatsoever; if none, then the tool was deferred for assessment since the only other information available was developer marketing and advertising literature, and the authors felt it inappropriate to rely on secondary knowledge to complete the initial assessment. Using these criteria the subset of 43 tools was reduced to 13, shown in Table 2.

Regardless of which tools were selected for immediate evaluation, the recommendation is for the 43 tools to be assessed against the forthcoming attributes, either by a user or the developer, because of the TSE capability they potentially bring through individual use or in concert with other tools.

Table 2 TSE tools and processes for immediate evaluation

Tool/Process	Developer
AAMODAT	ARDEC
ASEC	TARDEC
ATSV	PSU-ARL
CPAT	PEO-GCS
Excel	Microsoft
FACT	GTRI
JMP	SAS
MATLAB	Mathworks
ModelCenter	Phoenix Integration
OpenMDAO	NASA
R	R Foundation
TIES	ASDL, Georgia Tech
WSTAT	PEO-GCS

Notes: AAMODAT = Armament Analysis Multiple Objectives Decision Analysis Tool; ARDEC = US Army Research, Development and Engineering Center; ASDL = Aerospace Systems Design Laboratory; ASEC = Advanced Systems Engineering Capability; ATSV = ARL Trade Spaec Visualizer; CPAT = Capability Portfolio Analysis Tool; FACT = Framework for Assessing Cost and Technology; GTRI = Georgia Tech Research Institute; NASA = National Aeronautics and Space Administration; PSU-ARL = Pennsylvania State University Applied Research Laboratory; PEO-GCS = Program Executive Office Ground Combat Systems; TARDEC = US Army Tank Automotive Research, Development and Engineering Center; TIES = Technology Identification, Evaluation, and Selection; WSTAT = Whole System Trades Analysis Tool

The full set of rationale for keeping or rejecting a tool for the present or follow-on assessment is provided in Appendix B.

4.3 TSE Tool Functionality

After applying the filter criteria, the entire landscape of tools was revisited to see if each tool could be assigned a primary function. The purpose for this was 2-fold: determine how many decision analysis tools had been carried over for assessment, and address the observation that all of the tools appeared to be meeting a repetitive set of functions. The apparent functions are shown in Table 3, along with a brief description and the number of tools that have the function as their primary and secondary. As expected based on relying on the OR/MS DAS tool surveys for tool input, decision analysis tools made up a large portion of the initial tool landscape for this assessment. It should be noted that although a multidisciplinary optimization (MDO) function is specified in Table 3, ERS is not focused on identifying an optimum system but rather on assessing resilience across multiple use cases.

Table 3 TSE tool functionality

Function	Short Description of Function	Tools with Primary	Tools with Secondary[a]
Capturing Value	Using weightings, value measures, surveys, or other techniques to capture user-perceived value	3	9
MDO	Linking multidisciplinary models for the purpose of optimizing a constrained or unconstrained objective function	12	5
Statistical Data Analysis	Identifying trends or patterns in data, and developing models to help forecast outputs based on inputs	25	15
Visualization	Displaying information graphically with static or dynamic charts and tables	4	19
Decision Analysis	Evaluating sets of alternatives against preferences on outcomes	25	17
Project/Process Portfolio Management and Simulation	Assessing how much corporate value can be achieved from project portfolio combinations, resource allocation options, and scheduling	12	2

Notes: MDO = multidisciplinary optimization

[a]Not all tools have an explicit secondary function.

While the tools conveniently fell under these 6 primary function categories, they should not be considered to perform only these functions. Tools can readily be differentiated from each other when considering lower-level functions such as process simulation, data mining, regression, decision trees, brainstorming, Monte Carlo simulation, sensitivity analysis, and requirements analysis.

4.3.1 Capturing Value

Quantifying the value of system attributes, metrics, and goals based upon user perspectives allows for mathematical processes to logically operate upon these values. Quantified values help set the basis for decision analyses at the conclusion of TSE. Capturing perceived value enables multiple, potentially competing, stakeholder preferences to be modeled. The purpose of capturing value is not to over-constrain the capability space and find the "gold plated" system that maximizes value for all stakeholders simultaneously; understanding where stakeholders place

value illuminates the tradeoffs that must be addressed and reveals capability space that may be a best compromise for all. Tools that facilitate capturing value do so by eliciting weights, typically in such a way that quantitative or qualitative surveys address mathematical independence conditions. Other methods and tools involve mapping the logical flow of ideas or building scenarios and storyboards.

4.3.2 Multidisciplinary Optimization (MDO)

Typical systems engineering practices call for analyses within multiple disciplines. What might be an optimal solution to an aerodynamicist could very well be the poorest solution to the structures engineer. It is common for designs to pass from one engineering group to another, making modifications along the way in an iterative process. MDO is a technique whose goal is to streamline this iterative process and apply optimization algorithms while maintaining input from subject matter experts. Multiple tools such as computational fluid dynamics, computational structural dynamics, and statistical analysis software are linked together to create a centralized global system analysis model where results are automatically passed from each analysis to the next with little-to-no user interaction. MDO has the capability of multifidelity analyses in that it is at the engineer's discretion as to how many analyses are used, and their depth of detail. This allows the advantages of MDO to be applied in the preliminary concept design phase, all the way down to component level design. With MDO, the tradespace can be generated and explored repeatedly and at varying levels of fidelity to drive the system development process toward the optimal solution in an efficient, integrated manner. It should be noted that although an MDO function is specified in Table 3, ERS is not focused on identifying an optimum system but rather on assessing resilience across multiple use cases.

4.3.3 Statistical Data Analysis

Statistical data analysis forms the core of TSE. Decision makers at multiple hierarchical levels desire to find relationships in their data to draw conclusions and help predict future outcomes under uncertainty. Tasks such as design of experiments (DOE), surrogate modeling, Monte Carlo simulations, machine learning, and pattern recognition are used to reveal known, and discover unknown, relationships in data. These techniques also provide the basis for certain data visualizations that can aid decision makers in finding trends and points of interest within data, which would not otherwise have been found.

4.3.4 Visualization

TSE would be incomplete without communicating insights of a complex data set in an intuitive and graphical manner. Data visualizations incite discovery of information such as trends, inflection or saddle points, and statistical properties. The ease at which useful observations can be made, without mathematically heavy statistical analysis, presents potential to uncover new relations and can be used to drive further analyses. With a wide range of tools of varying customizability and price, an engineer would be remiss to omit a data visualization tool from their analysis package as it can be used to support other TSE functions such as decision analysis.

4.3.5 Decision Analysis

The primary reason for comparing alternatives is to eventually make a selection based on the information at hand. Alternatives are assessed for how well they perform in satisfying an overall preference. The process of decision analysis relies on stakeholder input, alternative analysis, and an overall comparison of how well alternatives meet objectives. Decision analyses can consist of simple forms of weighing pros and cons for each alternative, or be as complex as necessary to reach a decision with as little ambiguity as possible. A formal decision analysis process can show the uncertainty of a solution and its probability to meet goals by using single- or multiobjective utility functions that quantify the success of a given choice. Decision makers commonly rely on visualizations and statistical analysis results to make an informed decision, making presentation of analysis results critical.

4.3.6 Project/Process Portfolio Management and Simulation

Driven by the need to maximize corporate value under resource and schedule constraints, companies often rely on project portfolio management tools to design and simulate portfolio investment strategies. Included in this category are tools that perform process flow optimization (e.g., service industry modeling or assembly line throughout). Often, these tools rely on a structured value assessment process where corporate objectives are defined and quantified, alternative outcomes are assigned a probability of occurrence, portfolio elements are mapped to corporate value functions, and stochastic simulations reveal probability of success.

Interestingly, the categories identified here through observation closely matched the categories developed for a workshop on Data Driven Tradespace Exploration and Analysis organized by ARL and hosted by the Potomac Institute for Policy Studies[14], shown in Table 4.

Table 4 Tradespace workshop technical areas and tool functions

Tradespace Workshop Technical Area	TSE Tool Function Analog
Broaden, Populate, Manage	N/A
Link	MDO
Search, Explore, Analyze	Statistical analysis, visualization
Act	Capturing value, decision analysis

Notes: MDO = multidisciplinary optimization; N/A = not applicable

4.4 TSE Tool Attributes

Continuing with the reduced set of tools, the next task was to identify attributes that constitute a TSE tool and define the functionality desired in such a tool. Referring back to the sources in Section 4.1, an initial set of 25 attributes was developed, shown in Fig. 2.

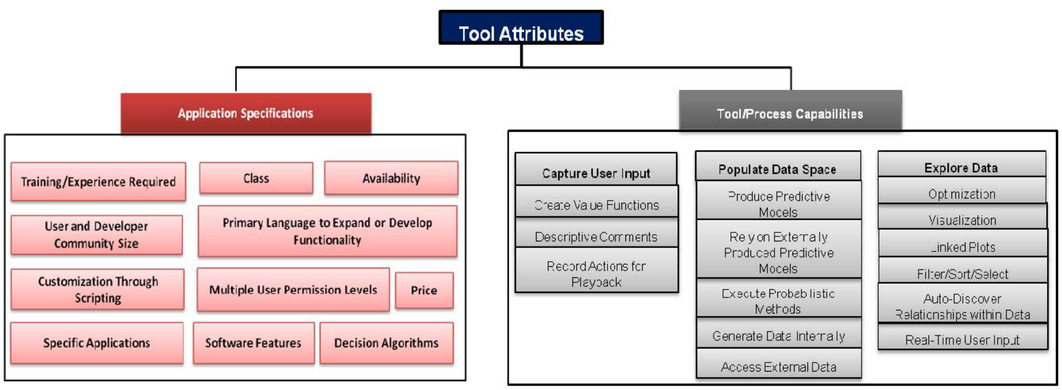

Fig. 2 Initial set of TSE tool attributes

Other sources were then reviewed in the areas of visualization, optimization, and value[15–20] and the industry surveys[5–7] were more thoroughly reviewed given their popularity and the quality in their results based on the assumed standardization of their questions and corresponding attributes.

An interesting discovery was made when attempting to validate the assumed standardization. The OR/MS Today DAS tool surveys are set up as online questionnaires. A hyperlink is provided for tool vendors and developers to describe their software by entering in yes ("y"), no ("n"), or a limited textual description. The 2010 DAS survey[5] did not provide rationale or descriptions of the survey questions.

There was also no indication of the provenance of the questions, other than a short statement about the industries from which new questions were pulled: "For this year's [2010] survey...questions based on the input of decision analysis practitioners from government, airline, oil and gas and pharmaceutical sectors were added." As an aside, 4 types of DAS materialized from the results of the 2010 DAS tool survey results[5], which also closely resemble the functions identified in Table 4:

- Problem structuring and brainstorming
- Multiobjective decision analysis, multicriteria decision analysis, analytic hierarchy process, and expert systems used to prioritize a list of existing options
- Single attribute decision making with uncertainty
- Uncertainties and probabilistic assessments, plus forecasting, optimization, and operations research

In the 2012 DAS tool survey[6], the same questions were provided to the vendors who had responded in previous years, as well as to vendors familiar to the survey moderator—not unlike what was done in this assessment when filtering for tools to include for immediate evaluation.

An electronic mail inquiry sent to the 2010 and 2012 DAS tool survey moderators revealed that the origin of the survey questions most likely traces back to a single individual, and there is no recorded pedigree on the questions or attributes, nor are formal, objective, unambiguous definitions available. Further, each moderator responsible with delivering the survey in a given year is permitted to update attributes as they see necessary (e.g., when technology advances result in a question or attribute being no longer applicable). Lastly, the tool vendors are permitted to "self-assess" their product's capability against the attributes, meaning the attributes are open to interpretation by those completing the survey.

Based on the above description of the DAS tool surveys, the authors of this report have recommended to the Institute for Operations Research and the Management Sciences that the 2014 OR/MS Today DAS survey moderator consider standardizing the questions and attributes by developing unambiguous definitions, possibly using the work performed here as a starting point.

After revisiting the initial TSE tool attributes, the set increased to 91, practically eliminating the ability to perform a VFT approach at this stage. The attributes were then grouped into common, higher level affinity categories, which are shown in Table 5 with a short description and the number of attributes per category. It should be noted that these categories are a mix of quantitative and qualitative, including binary (e.g., y or n), enumerated (e.g., small, medium, large), textual, currency, and integer.

Table 5 Top-level TSE tool attributes

Category	Short Description of Category	Number of Attributes
Class	Is the product better classified as a tool, or a process	2
Usage	Industries, market segments, or applications the is tool used in	3
Operating systems	On which operating systems can the product operate	6
Pricing	What is the price, or pricing structure, of the product	4
Training classes offered	What training options available for the product	4
Training/experience needed	Knowledge level of subject matter to effectively use the product	3
Software attributes	Limitations, expandability, and help options	8
Applications	Decision making, preference, risk, and uncertainty capabilities	8
Software features	Meaningful functions and user experience	34
Decision algorithm implemented	How does the product rank order alternatives	3
Availability of graphical elicitation techniques	How does the product capture values and preferences	9
Types of output display	How does the product present results for manipulation	7

The full set of attribute categories and their corresponding descriptions and rationale are provided in Appendix C.

A key capability worth noting is the expansion of a tool's functionality through custom coding/programming/scripting, or integrating code developed by others. The significance of this capability can readily be appreciated when understanding that a tool that supports customization through programming can be modified to include any conceivable function if the user has the time and knowledge to perform the programming. A familiar example is the ubiquitous Microsoft Excel[21] spreadsheet software. The built-in functionality of this tool is primarily for tabulation and charting of data, statistical analysis, and numerical solving. However, if familiar with the Visual Basic for Applications (VBA) language, the user can expand and customize Excel to perform any of the primary and lower-level functions described above.

4.5 TSE Tool Survey

With the tools and attributes identified, the next task was to essentially self-take the survey for the 13 tools in Table 2. Based on author knowledge of the tools and how well they met the attributes, the initial survey was completed with results provided in Appendix D. Even with detailed knowledge and experience on a majority of these tools, gaps still existed in the assessment related to pricing as well as some of the attributes pulled in from the DAS Surveys. The latter is driven by attribute ambiguity and subjectivity as explained earlier.

It is envisioned that the TSE Tool Survey will be fully populated by calling upon experienced users, and possibly developers, of the identified tools. To do this, the tool attributes query should be formatted as a questionnaire. The questions should follow survey best practices, being as specific and concise as possible to remove ambiguity and bias.

An important conclusion from this survey can be drawn based on the holistic view of TSE as described thus far: having a valid set of attributes, and an understanding of how a cross section of tools can satisfy them, is insufficient. What is now needed is a deeper understanding of how these tools are used and, more importantly, how they can be used when performing TSE in support of the decision analysis process. Gaining this understanding will enable users to better assess if they possess the appropriate tools for the TSE steps that they need to perform, as well as which TSE steps are capable of being performed given the tools in the user's possession.

5. Tradespace Analysis Decision Classification

This portion of the effort involved looking across several prominent TSE research activities to determine if there exists a common, best practice process for performing TSE. From these efforts, a consolidated process was outlined and steps compared across the ERS DPs and 2 other activities of interest to determine whether these efforts were consistently performing a TSE process and, if not, which steps were being omitted. A recommendation is offered for mapping TSE tools to attributes and to process steps.

5.1 TSE Process Audit

Thus far, tools were identified that may be useful in performing TSE, documenting their main functions, and collecting their defining attributes. However, these tools are intended for use across the system development life cycle, in the context of a process for performing TSE and making decisions. Therefore, it is important to understand how these tools can be intentionally used to support a consistent TSE process.

TSE research activities across government and academia were investigated to look for commonality in process execution, shown in Table 6. Additionally, TSE projects under study within the government (Table 7) were investigated to better understand what steps were being executed across the full TSE activity. Detailed descriptions of the three DPs are provided in Appendix E. Detailed descriptions of Capability Portfolio Analysis Tool (CPAT) and Framework for Assessing Cost and Technology (FACT) are provided in Appendix F and Appendix G, respectively. Due to limited availability of information, DP3 was not investigated.

Table 6 Prominent TSE research activities

Organization	TSE Activity	Reference
Georgia Tech ASDL	Integrated Reconfigurable Intelligent Systems Design Process	[22]
DSTA	Tradespace Exploration for Military Simulations	[23]
MIT	Responsive Systems Comparison Method	[24]
USMA	Expanding the Tradespace	[25]
PSU-ARL	Visual Steering Commands for Tradespace Exploration	[26]
NRL	Goal-Oriented Computational Steering	[27]
NASA	Visualizing Requirements and Risk	[28]

Notes: ASDL = Aerospace Systems Design Laboratory; DSTA = Singapore Defence Science & Technology Agency; MIT = Massachusetts Institute of Technology; NASA = National Aeronautics and Space Administration; NRL = US Naval Research Laboratory; PSU-ARL = Pennsylvania State University Applied Research Laboratory; USMA = United States Military Academy

Table 7 Projects investigated for TSE best practice

Organization	TSE Activity	Reference
AFMC	DP1: Fixed wing aircraft (Global airliner C-X)	[8]
NSWC	DP2: Ship design (Littoral combat ship)	[9,10]
ERDC	DP3: Sensor systems	...
PEO-GCS	CPAT	[29–31]
GTRI	FACT	[32,33]

Notes: AFMC = Air Force Materiel Command; CPAT = Capability Portfolio Analysis Tool; DP = demonstration project; ERDC = US Army Engineer Research and Development Center; FACT = Framework for Assessing Cost and Technology; GTRI = Georgia Tech Research Institute; NSWC = Naval Surface Warfare Center; PEO-GCS = Program Executive Office Ground Combat Systems

5.2 TSE Process Steps and Coverage

From the research activities in Table 6 and pilot projects in Table 7, a set of 12 common steps emerged, as shown in Table 8. It is assumed that these steps can be considered "TSE best common practice", although this assumption is not tested here. The steps are not presented in flowchart format to stress that a formal TSE process is not being proposed but rather existing processes consolidated.

Table 8 TSE best common practice steps

Step	Description
1	Determine mission scenario(s) and their requirements, and keep them open as long as possible
2	Identify set of operational performance characteristics and high level system design variables that impact operational requirements
3	Apply operational engagement models against various mission scenarios and threats to identify requirements, measures of performance, measures of effectiveness, and other performance metrics
4	Expert knowledge teams determine values of measures for given mission scenarios and requirements
5	Break down stakeholder values into roles, attributes, and specific tasks
6	Generate alternatives that meet requirements and constraints, and map stakeholder values to system design variables using scalable multiphysics based modeling design tools
7	Create reduced-order surrogate models to show iterative ability of adjusting scenarios and requirements to physical feasibility
8	Qualitatively or quantitatively rank how alternatives meet measures
9	Perform a life cycle cost estimate and life cycle schedule analysis of the system
10	Perform an optimization study to determine the optimum feasible space that meets all constraints and for each course of action
11	Determine courses of action based on optimal feasible space and perform postanalysis studies (operational impact and gap analyses)
12	Perform case studies to test for robustness and to make sure that the alternative solutions are resilient in changing operational environments

The TSE approaches of the ERS DPs in Table 7 were compared to the steps in Table 8 to determine if these pilots were indeed good representations of TSE best practice.

The results of this assessment are provided in Figs. 3 and 4. Shown across the top of the figures are the steps from Table 8. Shown down the left side of the figures are the activities from Table 7. In the center of the figures are blocks indicating which tools are used to perform the step within each activity. In some cases the tool is not applicable; this indicates that external information was provided or that the step was conducted internally to the activity without reliance on an explicit, external tool. Adjacent blocks showing the same tool indicate discrete steps within the activity that are using the same tool (e.g., Microsoft Excel in CPAT). DP3 was not mapped to the TSE steps in this study, but should be addressed in future work.

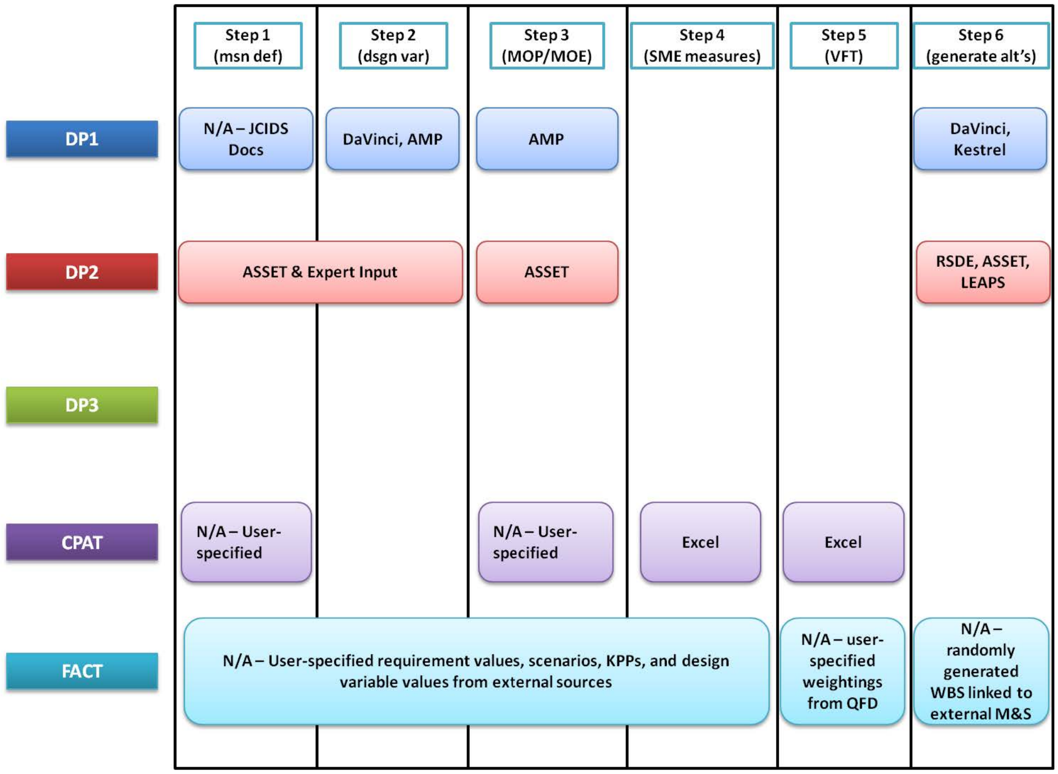

Fig. 3 TSE activities and their mapping to TSE common steps 1–6

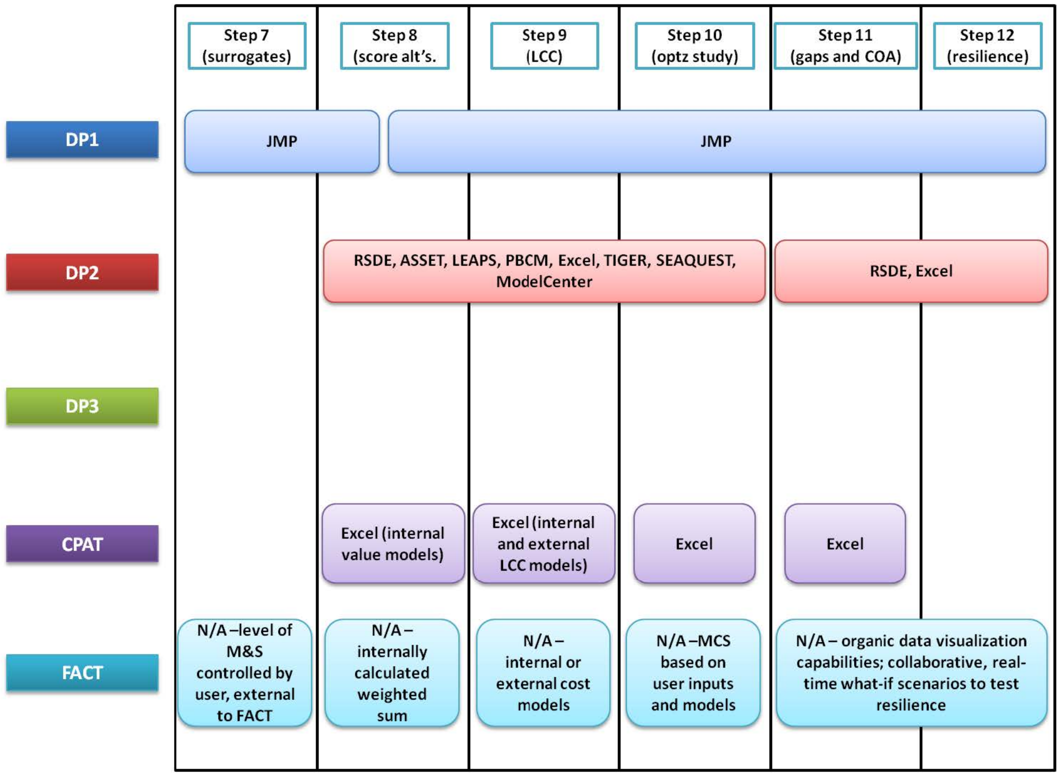

Fig. 4 TSE activities and their mapping to TSE common steps 7–12

The consolidation and subsequent comparison to select projects revealed that: 1) TSE is commonly performed in steps, as assumed; 2) there exists no formal, singular, consistent process for performing TSE across the organizations represented by the activities in Table 7; 3) there exists no singular step within TSE processes that performs the action of "exploring" a tradespace (when such an action is performed it is done so using prerequisite inputs from multiple steps while simultaneously feeding back, and forward, exploration results to the decision analysis process); and 4) the evaluated ERS DPs both omitted steps 4 (subject matter expert measures) and 5 (stakeholder value).

Also from Figs. 3 and 4, it can be seen that while CPAT does take into account value (step 5), it does not have an established method or tool for identifying operational performance characteristics and high-level design variables that impact operational requirements (step 2); these attributes are absent based on CPAT's role as a portfolio modernization investment decision-making tool as opposed to being an iterative design and optimization tool that links user preferences to design capabilities.[30] FACT, on the other hand, while not allowing real-time definition of system

design variables (step 2), does map the variables to system functions and physical components and defines their uncertainty, with the aid of a work breakdown structure (WBS) and random distribution assignments.[32] However, unlike CPAT, FACT does not support real-time allocation of stakeholder values to roles, attributes, and specific tasks (step 5). The two DPs do not perform an optimization study as part of a discrete step (step 10), but rather they roll optimization into a process that calculates alternative capabilities while simultaneously looking across capability gaps.

Of all of the efforts, FACT is the closest in terms of completely performing the best practice TSE steps. However, there is room to improve the level of interaction between the users and the tradespace; in some steps the inputs are generated within FACT (not with a specific tool) and in other steps FACT relies on static information provided by the user.

5.3 TSE Steps, Tools, and Functions

Consider that each of the 81 identified tools, defined by a subset of the 91 identified attributes, gives users an ability to perform many of the 12 identified TSE best practice steps. The fully populated TSE Tool Survey will provide a link between TSE best practice steps, tools, and functions, allowing users to balance their TSE needs with their organizational capabilities and constraints. The survey will serve as a database that can be used in different ways: users can decide which tools they should invest in by selecting the TSE steps that they desire to perform; or users can identify which TSE steps can be performed with the tools currently available within their organization. Knowledge level, budget, and training can serve as filters in the user's decision process. A recommendation for future research is to develop a decision analysis style user interface for aiding users in downselecting the most appropriate tools based on their TSE needs and goals.

6. Conclusion and Recommendations

This effort used attributes of TSE tools and the steps in a notional TSE process to illuminate relationships between tool capabilities and process steps to help existing projects within the ERS TSE Pillar understand if they are sufficiently and consistently performing what is considered to be necessary TSE for ERS. Although a specified (or default standard) formal TSE process is not in use for DOD programs, this effort has provided insight into a possible standard TSE process for ERS programs. The notional process requires further investigation to determine if it makes an improvement over current TSE processes. Multiple tradespace efforts in government and industry were reviewed for TSE tools, TSE tool attributes, and TSE process steps. A holistic view of 81 candidate tradespace exploration tools is provided. Tools were grouped into common primary functions. Ninety-one tool attributes were identified. A survey template was created based on an existing decision analysis tool survey, and the survey was populated for several tools.

Recommendations for future work include the following:

- Conduct a more formal VFT approach, developing value measures for attributes and functions.
- Refine the list of attributes and tools identified in this effort.
- Complete the mapping of tools to attributes through a survey of experienced users and developers. Request rationale to support the survey entry. Possibly request an ordinal ranking of how well each tool meets each attribute for subjective inputs to mimic the surveys referenced within this paper.
- Validate the TSE steps identified in this effort.
- Encourage the Institute for Operations Research and Management Sciences to adopt the attribute definitions developed here for their next OR/MS Today DAS survey.
- Develop a decision analysis style user interface to make the database interactive for the user.

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Appendix A. Tools, Definitions, and Descriptions

@RISK (Palisade) is an add-in to Microsoft Excel spreadsheet software that performs project risk analysis using Monte Carlo simulation. Based upon user inputs, outputs, and models, users can specify ranges and distributions on inputs as well as the number of trials. The tool determines the probability of outcomes and presents the results in tabular and plot format. Results are commonly presented to users as probability density functions (PDFs) and cumulative distribution functions (CDFs). Options for optimization, time series analysis, correlations, and curve fits are included in the tool. @RISK enables a user to plan for probabilistic outcomes based on input conditions and process randomness. Primary applications are resource allocation and scheduling.

1000Minds (1000Minds Ltd) is a multicriteria decision-making tool that is accessed through an Internet browser. As of the compilation and writing of this report, the 1000Minds web page was not operational. The 1000Minds tool is based off of pairwise comparisons and implements the method known as potentially all pairwise rankings of all possible alternatives. Primary applications are prioritization and resource allocation, but 1000Minds can also be used to determine decision maker weightings on alternative attributes.

Advanced Systems Engineering Capability (ASEC) (US Army Tank Automotive Research, Development and Engineering Center [TARDEC]) is a web-based integrated systems engineering knowledge creation and capture framework built on a decision centric method, high quality data visualizations, intuitive navigation that enables continuous data traceability, real-time collaboration and knowledge pattern leverage supporting the entire system life cycle.[1] ASEC is a single framework that enables systems engineering knowledge producers and consumers to create, capture, share, analyze, and present decision makers with systems engineering life cycle knowledge to improve decision quality and confidence. The government-owned framework has been architected to support model-based engineering and model-based systems engineering (MBSE) information. ASEC leverages a decision model as the integrative mechanism that provides context for its other system models, including: math/physics, architecture, life cycle ("ilities"), and roadmap. ASEC includes capabilities to capture stakeholder needs, manage system requirements, perform decision making, and track program risks and opportunities.

[1] After the study period, ASEC was renamed to the Integrated Systems Engineering Framework. New capabilities were added that are not included in this report.

The feature in the ASEC framework most applicable to the present study is the decision analysis tool. ASEC allows for the dynamic and visual analysis of alternatives by linking requirements, decisions, alternatives, and capabilities. The decision analysis tool supports the analysis of alternatives process including scoring of alternatives (solutions) against criteria, comparing the relative effectiveness of these alternatives (through spider, tornado and trade-off charts) and capturing the selection/rejection rationale for each alternative.

AgenaRisk (Agena Limited) uses Bayesian networks to perform diagnostic and predictive reasoning about uncertainty on stochastic models. Monte Carlo simulations can be run on user-specified probability tables. Outputs include tables and plots of distributions that allow users to visualize the probability of outcomes in PDFs and CDFs. Applications include business risk, strategic planning, procurement risk, safety, and reliability.

Analytica (Lumina Decision Systems) is a graphical modeling environment that uses influence diagrams to explain how variables interact. The graphical modeling technique is meant to eliminate confusion or hidden links that would typically reside in spreadsheet-based models. Users can analyze risk and uncertainty with Monte Carlo simulation, perform optimization, and perform data analysis. Users can expand the capability through existing libraries, or code their own functions in the C programming language. Analytica has been applied to engineering, business modeling, pharmaceuticals, financial planning, and more. Lumina offers training, or can visit a work site for more customized training.

Analytics (SAS) is a commercial grouping of software from SAS covering predictive analytics and data mining, visual analytics, forecasting and economics, operations research and optimization, model management and monitoring, quality improvement, statistics and text analytics. SAS proposes different software suites, individual programs, and program plug-ins for each of these areas. Each software solution from SAS caters toward different industry fields, levels of expertise, and analysis goals of the user. The user community includes groups from local to international levels that are often supported by SAS via workshops and conferences.

ARL Trade Space Visualizer (ATSV) (Pennsylvania State University Applied Research Laboratory [PSU-ARL]) is a visualization tool designed in Java to help users interact and dynamically explore complex tradespaces. ATSV can generate

scatter plots, scatter matrices, histograms, 3-D glyph plots, and Pareto frontiers that can be dynamically filtered and selected to implement a visual steering command, which allows a user to narrow a search to a chosen localized region of data. As of 2010, Penn State's ARL has made ATSV freely available for anyone to download and use. Some capabilities of this tool have been licensed to Phoenix Integration for use in the VisualizationPak in their ModelCenter software.

Armament Analysis Multiple Objectives Decision Analysis Tool (AAMODAT) (US Army Armament Research, Development and Engineering Center [ARDEC]) was created by the System Decision Analysis Group of the US Army Armament Research, Development and Engineering Center (ARDEC) in an effort to compare multiple systems across 5 categories: unit cost, operations and support (O&S) cost, performance, schedule, and growth potential. AAMODAT runs within Microsoft Excel spreadsheet software and is designed to walk the user through a value-focused thinking (VFT) approach. AAMODAT requires user inputs for objectives, value functions, swing weights, and priority weightings. Users define their systems using quantitative values for each system attribute, along with PDFs to capture uncertainty in system capability. The 5 output categories can be plotted in various ways, or users can display value functions on a radar chart. Sensitivities can also be performed to determine the robustness of the analysis outcome. AAMODAT uses Palisade's @RISK tool to conduct Monte Carlo simulations.

Berkeley Madonna (UC Berkeley) is a differential equation solver developed under funding from the National Science Foundation and National Institutes of Health. The tool can perform root finding, curve fitting, sensitivity analysis, and optimization. Outputs include tables and plots. Currently written in C, the developers have moved to a Java user interface with a C execution engine, and are soon including Python scripting capability.

Capability Portfolio Analysis Tool (CPAT) (Program Executive Office Ground Combat Systems [PEO-GCS]) was developed to provide a formal, structured process to address the difficulty associated with the decision analysis process within fleet modernization. CPAT follows a VFT approach, which involves decomposing weighted roles into functions and then using a mixed integer linear programming optimization model to develop portfolios of systems that maximize fleet value over time while meeting cost and schedule constraints.

Developed in VB.NET, CPAT helps establish the best mix of existing vehicles for a particular mission based on performance (how well a vehicle's performance meets weighted attributes), cost, and schedule constraints, and then reports the operational impact, and out year courses of action (COAs) based on funding distribution inputs. There are separate performance, schedule, and cost modules. A thorough review of CPAT has been performed by the Naval Postgraduate School.[2]

CPAT aids in decision making for portfolio resourcing by determining the "bang for the buck" of alternative platform mixes. The objective is to maximize fleet performance for a given role subject to constraints for budget, schedule, and minimum/maximum allowable vehicle numbers. For a series of assumptions on vehicles, roles, availability, etc., multiple COAs can be explored. The budget constraint is input into the tool (any or all costs; acquisition, research, development, test, and evaluation (RDT&E), O&S and the performance versus time is determined for each funding level (the COAs).

The tool provides fleet composition over time and cost breakdown per mission per cost metric per year. There are 3 parts to the tool:

1. Performance Module. Value of the fleet mix comprises roles that must be performed by vehicles, and each role is assigned a mix of vehicles. These roles are decomposed into major attributes, and these major attributes all have measures. Weightings of the attributes are determined using a swing weight matrix, and weightings of the roles are obtained through pair-wise comparison. Single utility functions (SUFs) are generated from subject matter expert input for each measure in each role. Vehicle performance is then analyzed for each role, and these performance data serve as input into the SUFs to convert performance into utility. Each major attribute for a vehicle in a role is then determined by summing each SUF, which is a function of performance, multiplied by the attribute's weighting. Each vehicle for a role is then a sum of all of the major attribute scores.

2. Schedule Module. Fleet mixes are predefined, as are availability by vehicle by year.

[2]Ewing L, Dell RF, MacCalman M, Whitney L. Capability portfolio analysis tool (CPAT) verification and validation report. Monterey (CA): Naval Postgraduate School; 2013 Jan. Report No.: NPS-OR-13-001.

3. Cost Module. Cost metrics were developed to represent the life cycle expectations, and attempted to capture the RDT&E, procurement, and O&S costs. These are not life cycle cost (LCC) estimates, but rather metrics by which to rank vehicle alternatives.

Classification and Regression Trees (CART) (Salford Systems) is a commercial classification tree tool used for data mining to quickly reveal data relationships. It is based upon the mathematical classification theory by Jerome Friedman and Leo Breiman. Generally, the CART method maps observations about an outcome to conclusions about the outcome's target value. CART models can be translated into SAS, C, Java, and Predictive Model Markup Language languages for implementation into other analysis software. Salford Systems offer online and in-person training and support.

ClearPoint Strategy (Ascendant Strategy Management Group) is a strategy management tool that links business actions and decisions to business strategy goals. Projects, measures, and objectives can all be linked and tracked. The tool contains organic charting capabilities but also exports to the Microsoft Excel spreadsheet software. Ascendant offers help videos and documentation free on their web page, and also offers both in-person and online training.

Comparion Suite (Expert Choice, Inc.) is a web-based tool for conducting resource allocation and strategic planning. The tool appears to aid in portfolio prioritization. The company website provides very little information on the tool's capabilities. Interested parties must provide contact information to download information.

CyDesign Studio (CyDesign Labs) is a model-based design optimization platform for 0-D and 1-D multiphysics analysis. Models are developed in the open source Modelica language and compiled within the CyDesign tool. CyDesign Labs was purchased by ESI Group in October 2013. CyDesign Studio integrates requirements management, design space exploration, modeling, Modelica simulation, tradespace studies, parametric optimization, verification, and certification. Users can view their system in a hierarchical view and create interfaces between components. When the models are simulated, the user is able to see the estimated performance capability achievable by the system.

D3 (D3JS.org) is an open-source JavaScript library of data visualization options, allowing users to create dynamic and interactive visualizations. D3 is accessible through Internet browsers. The data for D3 can be in JavaScript Object Notation or comma-separated value format, or users can write JavaScript functions to read in other data formats. Essentially, D3 is a library of visualization overlays for data.

DEA SolverPro (SAITECH, Inc.) is based upon the textbook by Cooper et al.[3] Data envelopment analysis is a nonparametric method to estimate production frontiers. DEA SolverPro uses the DEA method to estimate the efficiency of production efficiency of an entity. DEA does not have an input/output function and instead assumes each entity has the capability to produce the same level of output and generates a new composite frontier from the best producers. The textbook referenced serves as the main training tool for DEA SolverPro.

DecideIT (Preference) is a graphical decision analysis tool centered on decision trees and criteria hierarchies. The tool appears to follow a structured decision analysis approach, with users defining their options, identifying decision criteria, assigning importance weightings, assigning risk levels, and conducting sensitivity analyses on ranked alternatives. DecideIT can handle multiple objectives, and different weightings assigned to each objective by different stakeholders. DecideIT displays relationships between options, objectives, and uncertainties to the user. Preference, a Sweden-based company, offers courses and seminars to train users in the use of their tools as well as in decision and risk analysis theories.

Decision Explorer (Banxia Software Ltd.) is an idea mapping tool that enables the user to visualize the reasoning, structure, and interdependence of their decision logic, potential outcomes, and risks. The focuses are idea mapping, scenario building, brainstorming, mind mapping, and influence diagramming. Banxia, a British company, offers free downloads of its manuals and tutorials, and a 1-day session on how to use the tool.

DecisionTools Suite 6.0 (Palisade Corporation) is a set of programs from Palisade Corporation that aide in decision making. The suite consists of @RISK for Monte Carlo simulations, PrecisionTree for decision trees, TopRank for "what-if" analyses, StatTools for statistical analysis, NeuralTools for neural networks and pre-

[3] Cooper WW, Seiford LM, Tone K. Data Envelopment Analysis: a comprehensive text with models, applications, references and DEA-solver software. New York (NY): Springer Science+Business Media, LLC; 2007.

dictive modeling, and Evolver and RISKOptimizer for optimization. All tools are integrated within Microsoft Excel spreadsheet software. Palisade Corporation provides regional training events as well as live web training and onsite training. Tech support and consulting services are also available.

Design Analysis toolKit for Optimization and Terascale Applications (DAKOTA) (Sandia National Laboratories) is an open-source toolkit that provides an extensible interface between analysis codes and a variety of iterative systems analysis methods, including optimization, uncertainty quantification, parameter estimation, and sensitivity analysis. DAKOTA is written in C++. DAKOTA operates on the outputs of a user's analysis codes or tools using built-in algorithms. Sandia provides free access to tutorials, examples, and other documentation. DAKOTA currently runs in a Windows DOS command prompt environment, but Sandia is developing a complementary graphical user interface (GUI). DAKOTA outputs basic statistics such as mean, standard deviations, and correlations. Tabular output can be passed on to any third party statistical analysis tool.

D-Sight Desktop (D-Sight Inc.) is multicriteria decision-making software that implements the Preference Ranking Organization Method for Enrichment Evaluation and Geometrical Analysis for Interactive decision Aid methods. The preference modeling process scores alternatives by comparison in pairs and generating a preference function that are used to assess the best alternative. D-Sight includes plug-ins to elicit user weightings for each criteria through an interactive process. D-Sight has capabilities to export reports to Microsoft Word and Excel office productivity software, as well as Adobe Systems Portable Document Format. It can conduct sensitivity analyses and produce data visualizations. D-Sight Inc. provides case studies, user examples, online tutorials, and documentation for training. D-Sight also offers D-Sight Web, a collaborative version of the D-Sight Desktop multicriteria decision-making software. D-Sight Web is accessible online and allows for collaboration from multiple users on the same project.

Enterprise Portfolio Simulator (ProModel Corporation) is a project portfolio planning, simulation, and managing tool based on the ProModel Corporation's Portfolio Simulator tool that provides a web browser based interface to allow for collaboration on multiple projects by multiple users. The discrete event simulations can be analyzed and optimized to improve project performance. Enterprise Portfolio Simulator can be connected with Microsoft Project project and portfolio management

software so that what if scenarios can be run and analyzed. ProModel Corporation provides online and classroom based training programs and provides online support.

Equity3 (Catalyze Ltd.) is a multicriteria decision analysis tool. An individual user constructs a decision model by assessing the cost and benefits of multiple criteria and has a graphical tool to elicit accurate weights for each. Equity3 allows for rapid what if analyses based upon given resources and provides a frontier of available options. Equity3 is geared toward budgeting and resource allocation decisions. Catalyze Ltd. provides 12-month support contracts that include unlimited technical support over telephone, email, and fax in addition to optional onsite assistance.

Eureqa Desktop (Nutonian, Inc.) was originally developed by Cornell University, but has transitioned to ownership by a private company. Eureqa uses symbolic regression to find linear and nonlinear mathematical relationships in data provided as rows and columns. The user can specify what operators to use (e.g., math, trig, logic, etc.) in the target expression, and Eureqa identifies the "simplest" mathematical relationship. Simplicity of the relationship is determined from the number of operators (e.g., addition, subtraction, power, etc.). Eureqa displays all identified equations. Eureqa for Excel started out as a free download and use tool, but recently there is a new Eureqa Desktop product that is installation-only and available for a free 30-day trial.

Excel (Microsoft) is a widely used data analysis and visualization tool. Users enter data in a row-column format and use built-in menus to operate on the data. With the Visual Basic for Applications (VBA) programming language, users can expand the capabilities of Excel to conduct any of the identified tradespace exploration functions. Many other tradespace exploration tools can export to or import from Excel-based files given its wide user base. Many vendors offer training, and there is a very large user community who share tips and tricks online.

ExtendSim Suite (Imagine That, Inc.) is a dynamic process simulation tool that allows users to predict the impact that changes will have on both new and existing processes. Users construct their models with the built-in "building blocks" and can execute their continuous or discrete processes deterministically or probabilistically. The tool provides visual feedback of the process execution as well as data analytics and charting capabilities. ExtendSim offers training videos on their web page, both

for their specific products and for general themes and functions that their products cover. There is a broken link to a user forum on the web page. ExtendSim has a network of "Expert Solutions Providers" that work with customers to apply ExtendSim products to their specific needs.

ForeTell (Decision Path, Inc.) is a GUI-driven project and portfolio management tool that allows users to build scenarios, execute the scenarios probabilistically, and then conduct statistical analysis on the results. Users establish the key performance indicators to track during simulation such that the results are displayed as likelihood of outcome for each indicator, per decision, per scenario. The top-level scenario planning approach is applicable to market penetration, disaster planning, and portfolio management. Help is available by contacting the company via email or phone.

Framework for Assessing Cost and Technology (FACT) (Georgia Tech Research Institute [GTRI]) is a government-owned, open architecture, browser-based framework for assessing performance and cost of mechanical systems, funded by the US Navy through the Marine Corps Systems Command. FACT uses systems modeling language (SysML) in an MBSE environment. FACT enables "near real-time analysis for exploring the design parameter trades that affect the overall performance, reliability, and cost of a system design."[4,5] FACT is hosted on a US Navy server and requires common access card (CAC) credentials to log in. Users map a system's work breakdown structure (WBS), in MIL-STD-881A format, to SysML block definition diagrams to represent the decomposed physical hierarchy in SysML. Performance relationships are captured in SysML parametric diagrams, and can be calculated using user-provided physics-based equations or tabular data. The user builds their system in a bottom-up fashion, by selecting components from a component library. Components must already be characterized with value properties (e.g., torque, power, mass, speed, etc.) by the user. These values are used as inputs to the parametric block diagram, which then links out to surrogates or modeling and simulation (M&S) tools. The outputs from the surrogate equations and M&S tools are then returned to FACT through the parametric diagram.

[4]Ender TR, Browne CD, Yates WW, O'Neal M. FACT: an M&S framework for systems engineering. Paper presented at: Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC). 2012 Dec 3–6; Orlando, FL.

[5]Ender TR. Model-based systems engineering as a collaborative web-service. Paper presented at: National Defense Industrial Association Ground Vehicle Systems Engineering and Technology Symposium (NDIA GVSETS). 2013 Aug 20–22; Troy, MI.

FACT contains a low level of computer-automated design compatibility; users can drag-and-drop an image file into the tool to "see" the part they are updating/modifying. Image files are linked to sections of the WBS so that the user can click on a part in the image and jump to that section of the WBS for editing values. FACT can instantiate many (thousands) system models using an internal algorithm that generates a WBS at random. Each WBS is then analyzed for its capabilities using user-provided data and models.

For tradespace exploration, users set threshold and objective values on key performance parameters, and with user-specified ranges and distributions on input variables FACT will produce PDF and CDF plots depicting the likelihood of achieving values of interest. FACT has organic plotting capability including scatterplots that allow highlighting of groups of points or filtering based on minimum/maximum plot axis values, as well as small multiples plots that allow comparison of outputs with each other.

Genetic Resources for Innovation and Problem Solving (GRIPS) (Aerospace Corporation) is a multiobjective decision support tool developed by the Aerospace Corporation and the Penn State Applied Research Laboratory. Development started as a single-objective optimization tool for National Security Space. The tool was later expanded to multiobjective optimization. GRIPS uses evolutionary algorithms for exploration (search) and exploitation (selection) of the most fit solutions; the nondominated set of solutions found on the Pareto frontier. There are 3 stages to the GRIPS decision support process:

1. Interviews
2. Multiobjective optimization
3. Visualization and decision making
   (a) Identify and understand design parameters, objectives, and constraints
   (b) Stakeholder models or other models are integrated into GRIPS
   (c) Pareto set is exported to the AeroVis tool for visualization through plotting in up to 7 dimensions

Internet searches for GRIPS result in patents, but there is scarce technical detail available via publications and case studies. Little information is available publicly after 2010.

GoldSim Pro (GoldSim Technology Group) is an add-in to the Microsoft Excel spreadsheet software that allows users to set ranges and distributions on inputs of Excel-based models. The product operates similarly to Oracle's Crystal Ball and Frontline System's Risk Solver Pro add-ins. After users establish the input distributions and the number of trials, histograms and simulation statistics are visible for review within Microsoft Excel. GoldSim Pro can conduct discrete and continuous event simulations after building systems with a hierarchical approach. GoldSim Pro is better suited for complex systems with loose interactions than it is for engineered systems with well-defined interactions.

gPROMS (Process Systems Enterprise Limited) is a model-based engineering approach for high fidelity predictive modeling in the process industry. gPROMS is a family of modeling software, with specific modules and libraries for multiphase fluid flow, fuel cells, depressurization, crystallization, carbon capture and storage, and molecular thermodynamics. Includes a wrapper that wraps gPROMS models and solvers such that they can be implemented in stand-alone analysis environments such as MATLAB. Appears to have the capability to develop custom models using the ModelBuilder tool, which allows drag-and-drop of hardware into a model canvas. From there, users can simulate the model, including uncertainty on inputs. Data analysis and visualization capabilities are unknown. Process Systems Enterprise offers in-person training as well as online support via a hypertext markup language form.

Hiview3 (Catalyze Ltd.) is a decision modeling tool that is effective as a collaborative tool supporting decision conferences and the evaluation of decision options. The modeling process is similar to Equity3 in that the decision tree is constructed followed by scoring criteria and analyzing the model to determine the recommended set of available options. Catalyze Ltd. provides 12-month support contracts that include unlimited technical support over telephone, email, and fax in addition to optional onsite assistance.

Iris (Ayasdi) is a commercial "insight discovery" data analysis software. It is a model-free and code-free data mining tool that runs through hundreds of algo-

rithms to identify relationships within data sets by using their unique topological data analysis approach. It has a cloud-based option to offload computations from the local user's machine. Its GUI provides visualization that graphically depicts links between data points in multiple dimensions. Its use in the medical industry found links between breast cancer survivors and their genetic makeup. Iris is purely a data analysis tool and does not provide any modeling or simulation capabilities. Ayasdi provides online product support.

Isight (Dassault Systèmes) is a commercial visual multidisciplinary analysis and optimization tool that is part of Dassault Systèmes' SIMULIA family of software. Isight provides a drag and drop workflow environment to integrate simulation models from multiple disciplines and software and automates the execution of simulations. The resulting data can be post processed with Isight to explore the design space and visualize the data. Optimization and design of experiments (DOE) can be applied to the workflow to automate the design and analysis of an optimal or best solution. Isight includes components that can interface with Microsoft Excel and Word office productivity software, MATLAB, Python scripts, SIMULIA software, and other third party analysis tools.

JMP (SAS) is a commercial statistical discovery program from SAS. JMP is very graphically driven and leans heavily towards interactive data visualization and statistical simulation. It does not focus on optimization. Exploratory statistical analysis can be used to identify trends and various plotting tools can graphically depict them. Models can be created through various probabilistic methods and can be analyzed through simulations and more plotting tools. JMP has scripting functionality for automating analyses and recreating results. JMP's analysis capabilities are selected from built in functions, no coding or scripting is necessary. It can interface with other software such as SAS, Microsoft Excel spreadsheet software, and R language programs. SAS offers online resources, community support discussions, live web training, and in-person training courses.

Joint Integrated Analysis Tool (JIAT) (Assistant Secretary of the Army for Financial Management and Comptroller) is a CAC-enabled, web-based system that provides a single log-on/user interface where analysts can search for, retrieve, normalize, and incorporate official validated data into their cost estimates and models. JIAT is government-only access and employs strategies to manage and control access to sensitive information under 3 main headings: databases, libraries,

and models. JIAT provides access to 8 major database sources, over 725 cost estimating relationships and factors, over 125 web links, and models from 4 major tool providers. JIAT's databases include ACDB, AMCOS, CKB, DAMIR, DCARC CSDR-SR, FLIS, FORCES, Government Rates, and OSMIS.

Users initiate a JIAT session, which is an instance of querying a database or running a model. Next, the user selects from a list of providers, which are the data and model sources, and JIAT displays the available data and models. The user will have to understand the inputs and outputs of the models, and have access to that data. Once a cost estimate is generated, JIAT results can be exported to Microsoft Excel spreadsheet software, CO$TAT, and ACE for further analysis.

JIAT can perform non-time phased or time-phased analysis to perform what-if and sensitivity analyses. Outputs are displayed in organic plotting services, or tabular data can be exported for analysis by a third party tool. Free training is offered periodically. The JIAT web pages provide access to a user manual, knowledge base articles, newsletters, and brown bag presentations.

KNITRO (Ziena Optimization LLC) is a nonlinear optimization solver implementing the Interior-point Direct algorithm, the Interior-point CG algorithm, and the Active Set algorithm. KNITRO is available with interfaces to multiple programming languages and computational tools such as C++, Python, MATLAB, Microsoft Excel, and Labview. Ziena provides support contracts that include software maintenance, usage support, and consultation (at additional cost).

Logical Decisions for Windows (Logical Decisions) is a decision analysis tool. It provides 7 methods for a user to apply weights to different system metrics, organizes metrics into a hierarchical chart, analyzes, and scores a system. No optimization or system selection is done with this tool. The results from a Logical Decisions for Windows analysis can be used to optimize about outside of this tool. Logical Decisions offers unlimited over the phone and email technical support as well as in person seminars and consulting services.

Logical Decisions Portfolio (Logical Decisions) is based on Logical Decisions for Windows. It is a decision analysis tool that analyzes a set of alternatives and can aid in selecting a set of solutions rather than a single solution. Cost and other metrics can be applied to portfolio alternatives and, combined with the rankings of each alternative from Logical Decisions for Windows, Logical Decisions Portfolio

applies an optimization algorithm to find the best solution. Logical Decisions offers unlimited over the phone and email technical support as well as in-person seminars and consulting services.

MapleSim (Maplesoft) is a commercial modeling and simulation software from Maplesoft. It uses an object-oriented style of model building by dragging and dropping components into the model. MapleSim automatically generates the model equations and can then run simulations and analyses. MapleSim uses the mathematical engine of Maple, which is another piece of commercial computational software developed by Maplesoft. The components in MapleSim are built from the Modelica open source modeling language. Maplesoft provides training videos, example models, online documentation and training courses.

Mathematica (Wolfram) is a commercial computational environment. It is similar to MATLAB but it uses a more visually interactive front end and has several features to produce stand-alone mathematical applications such as interactive data visualizations, interactive text books, and website applets. In the GUI, computations are displayed as notebook style documents. Mathematica has built-in functions for symbolic computation, optimization, data visualization, signal processing, statistical analysis, automated report generation, and more. Mathematica can link to other mathematical software packages including Microsoft Excel, MATLAB, and R. Other programming languages such as VBA and Python can connect to Mathematica. It is widely used in engineering, finance, analytics, and software development, and as a learning tool for academic math and sciences. Wolfram provides options for learning Mathematica online, in person, or by documentation.

MATLAB (Mathworks) is a commercial numerical computing environment and programming language from Mathworks. It can be expanded by add-on toolboxes ranging from statistical analysis to control systems design and more. Included with MATLAB is Simulink, a graphical block diagramming tool used for modeling, simulation, and analysis of dynamical systems. Simulink is typically used for signal processing and control systems design and testing. MATLAB is widely used in industry and academia. Users can create custom programs in a similar fashion as a standard programming language such as Python or C++. Programs can be exported to run without requiring a local installation of MATLAB software. Mathworks provides online support and training and many third party books and training courses are commonly available. MATLAB is similar in use to Maple from Maplesoft.

MedModel Optimization Suite (ProModel Corporation) is a planning and throughput analysis tool for the healthcare industry. The tool can analyze, visualize, and optimize the layout of a medical facility based on performance metrics specified by the user. Users can also pose what-if questions about the layout and its constraints, and the tool will provide options for improving the performance metrics. The tool has import/export capabilities with Microsoft Excel spreadsheet software. ProModel Corporation provides online and classroom based training programs and provides online support.

modeFRONTIER (Esteco) is a commercial software for multiobjective optimization and multidisciplinary optimization. It integrates with third party analysis software (e.g., Computational Fluid Dynamics [CFD], Computational Structural Dynamics, etc.) to create an environment by which the design process can be automated to optimize a design and provide data analysis and visualizations for design space exploration to aid in decision making. modeFRONTIER is comparable to ModelCenter in that it is an environment that links various analysis tools together to streamline and automate the design process. The modeFRONTIER environment sets up the design process for rapid design modification and re-simulation and analysis. modeFRONTIER is in use by many internationally recognized universities and corporations.

ModelCenter (Phoenix Integration) is a commercial graphical environment for systems engineering and optimization aimed at reducing life cycle cost and time. Several aspects of the engineering process (e.g., CFD and finite element analysis [FEA] analyses) can be linked together with ModelCenter to generate a design space that can be analyzed, explored, optimized and visualized. Probabilistic methods can be utilized to model high fidelity problems and then simulated to reduce time. Designs can be optimized through the use of 30 algorithms from leading research organizations. Interactive visualizations are also possible. ModelCenter captures the global system engineering process in one package. Phoenix Integration provides webinars, online support, training courses, and consultations.

Multivariate Adaptive Regression Splines (MARS) (Salford Systems) is a commercial nonlinear regression modeling tool. Its strength is the capability to capture nonlinear relationships using the MARS regression method. Regression models can be used for data mining applications. Salford Systems offers online and in-person training and support.

Nexus (iChrome Ltd.) is a commercial systems design optimization software similar in role to ModelCenter and modeFRONTIER. A GUI links each analysis in the design process. Third party tools such as Nastran, Abaqus, Fluent, ANSYS, and MATLAB can be linked to streamline and automate the design and analysis process. The flowchart module is a graphical representation of the design process and is where evaluation nodes can be linked to external software. The response surfaces module can create static and dynamic DOE and can create response surfaces. The visualization and post-processing module can create 2-D and 3-D charts to display results. Nexus is available for Windows and Linux and in local or scalable versions with free licenses available for academia and research purposes.

OpenMDAO (National Aeronautics and Space Administration (NASA) Glenn Research Center) is an open source Python based Multidisciplinary Design Analysis and Optimization (MDAO) tool. OpenMDAO has built-in functions for constructing and executing optimization and statistical analyses. Third party analysis tools can be integrated into an analysis model through built-in plug-ins or from user-created wrappers. OpenMDAO can provide multiple levels of fidelity through the number and fidelity of the analysis tools utilized by the user. The automation of analyses and optimization provides a streamlined method for design and analysis of systems. Python packages required for OpenMDAO also give numerical computation and data visualization capabilities. Given a user's level of coding expertise, OpenMDAO can function in a similar capacity to other MDAO tools such as ModelCenter. NASA Glenn is still actively developing and updating OpenMDAO and provides support tutorials, videos, and online discussion forums.

OptiY (OptiY GmbH) is a commercial software for multidisciplinary analysis and optimization. Similar to ModelCenter and OpenMDAO, OptiY has optimization algorithms and integrates third party analysis tools (e.g., MATLAB, ANSYS) to create a design environment to streamline the design process and aid in decision making. OptiY has a graphical flowchart style workflow editor where users can integrate external tools. It has data mining capabilities to identify trends and relationships within data sets. It can conduct local and global sensitivity studies and probabilistic simulations to characterize realistic system behaviors. OptiY can create metamodels or surrogate models to conduct virtual optimizations that can speed up the design process. Metamodels can be exported to C, Modelica, and even MATLAB codes for further simulations outside of OptiY. OptiY provides online tutorial videos and scripts for integrating several popular commercial analysis tools.

Portfolio Simulator (ProModel Corporation) is a strategic and tactical portfolio management tool. Users can operate the tool top-down by specifying their strategic corporate objectives, such as net present value and return on investment, and allow the tool to optimize on tactical and operational goals, such as facility metrics, resource loading, schedule, and more. Or the tool can be run in reverse (bottom-up). The tool integrates with Microsoft Project and Excel software. Decision trees, charts, and tables allow users to make decisions based on the outcomes. ProModel Corporation provides online and classroom based training programs and provides online support.

Process Simulator (ProModel Corporation) is a Lean Six Sigma and value stream focused tool. The tool is a plug-in to the Microsoft Visio flowcharting software to help manufacturers design and re-engineer their business and manufacturing processes. Users can create value stream maps, estimate product workflow outputs and times, and estimate resource loading required for meeting process metrics. The tool provides top-down views of processes such that the user can visualize movements and limitations of processes. The objective is to capture interdependencies through process simulation and optimization. ProModel Corporation provides online and classroom based training programs and provides online support.

Project Simulator (ProModel Corporation) is a scenario planning, simulation, and reporting add-in for the Microsoft Project software. Project execution interdependency and variability can be simulated and then plotted. Distributions can be set on project inputs and schedule impacts can be seen directly in the Windows-based project and portfolio management software. ProModel Corporation provides online and classroom based training programs and provides online support.

Promax Professional (Cogentus Consulting Ltd) is a project and portfolio management tool for determining combinations of projects or activities that meet budget constraints. Applications include prioritization and evaluation for choosing between projects, technologies, software, partners, or strategies. Promax contains a root cause analysis capability as well as an innovation and idea generation tool. The tool contains organic drawing and charting capabilities. Cogentus offers online video tutorials, within-product help menus, downloadable manuals, and other help documentation on their web page.

ProModel Optimization Suite (ProModel Corporation) is a discrete event simulation tool. The tool can analyze, visualize, and optimize on multiple scenarios related to supply chain, logistics, manufacturing, and operational scenarios based on performance metrics specified by the user. Users can also pose what-if questions about event-based occurrences of a process, and the tool will provide options for improving the performance metrics. The tool has import/export capabilities with Microsoft Excel spreadsheet software. ProModel Corporation provides online and classroom based training programs and provides online support.

R (R Foundation) is an open source programming language and environment for statistical computing and graphics. R by itself uses a command line interface but third party GUIs are available. R is extensible through installation of packages from a growing library supported by the open source community. R is based off of S, a commercially developed statistical programming language from Bell Laboratories. Most codes written in S will run through R without modification. R's strength is that it can produce high quality graphics for data visualization with relative ease. It can also be linked to C++ or Fortran code for computationally heavy programs. R is widely accepted and used for statistical analysis and visualization application in many industries. Documentation and learning tools are widely available in print and online without cost.

RandomForests (Salford Systems) is a commercial data mining tool that builds off of Salford's CART methodology. Its strength is the capability to generate and assess multiple decision trees such that variable importance can be ranked. The user must have familiarity with the structure of Random Forests, including the shape, predictors, and how to implement randomness in the generation of leaves. Salford Systems offers online and in person training and support.

Rank Inclusion in Criteria Hierarchies (RICH) Decisions (Systems Analysis Laboratory [SAL], Aalto University) is a web-based, Java decision support software based on the RICH method that is used to capture and analyze preferences. In the RICH method, the decision maker can specify subsets of attributes that contain the most important attribute or associate a set of rankings with a given set of attributes. It assigns alternatives a ranking in each of the desired decision attributes by asking the user to provide answers to, How well does alternative perform with respect to one attribute? and How well does one alternative perform with respect to all attributes? The tool allows users to provide lower and upper limits of alterna-

tive performance, as well as weight the attributes. The University provides limited help and limited documentation on their web pages. Their web pages are confusing, have poor documentation, and it is unclear how it fits into a larger suite of capabilities. RICH is a part of the Decisionarium site for interactive multicriteria decision support tools.

Rave (Aerospace Systems Design Laboratory [ASDL], Georgia Institute of Technology) is an open source decision support tool with capabilities of visualization, optimization, DOE, decision analysis, and surrogate modeling. Rave is a MATLAB toolbox and can interface with other computational scripts written in MATLAB because it is built upon MATLAB m-code. Rave allows a user to perform continuous or discrete visualization, letting the decision maker view the continuous impact of independent variables on dependent variables, as well as seeing the same design points in multiple, discrete views. Rave can generate surrogate models (artificial neural networks and response surface equations) of a data set for exploration of the design space. Rave cannot link multiple codes together. Rave can perform optimization through generation of new designs to meet objective functions, as well as through sorting existing designs. Rave has capabilities similar to ATSV, JMP, ModelCenter, and OpenMDAO.

Relational-Oriented Systems Engineering and Technology Tradeoff Analysis (ROSETTA) (ASDL, Georgia Institute of Technology) is a methodology to "bridge the gap between qualitative subject matter expert driven techniques and quantitative modeling and simulation techniques." This methodology utilizes quality function deployment (QFD), which is mapped to modeling and simulation processes. Surrogate models created through response surface equation (RSE) methodology model the relationships from QFD and also allow for Monte Carlo simulation of requirements. The ROSETTA methodology is targeted for use in the early stages of systems design to help quantitatively define design space boundaries and subject matter expert decisions.

RiskSim (TreePlan Software) is a Monte Carlo simulation add-in for the Microsoft Excel spreadsheet software. RiskSim provides random number generator functions as inputs for Excel-based models and conducts Monte Carlo simulation. TreePlan provides answers to frequently asked questions for their software.

Risk Solver Pro (Frontline Systems, Inc.) is an add-in to the Microsoft Excel spreadsheet software that allows users to set ranges and distributions on inputs of Excel-based models. The product operates similarly to Oracle's Crystal Ball and GoldSim Technology Group's GoldSim Pro add-ins. After users establish the input distributions and the number of trials, histograms and simulation statistics are visible for review within Microsoft Excel.

Robust Portfolio Management (RPM) Decisions (SAL, Aalto University) is a web-based Java tool for analyzing multicriteria portfolio problems. Users provide tabular data and enter the alternatives, attributes, value measures, and weights. The tool provides multiple built-in algorithms and visualizations, and supports interactive decision support. The University provides limited help and limited documentation on their web pages. Their web pages are confusing, have poor documentation, and it is unclear how it fits into a larger suite of capabilities. RPM is a part of the Decisionarium site for interactive multicriteria decision support tools.

Salford Predictive Modeler (Salford Systems) is a software suite that contains the CART, MARS, TreeNet, and RandomForests tools. The suite essentially performs the combined functions of the individual tools that comprise it, including data mining and regression, decision trees, and model construction. Salford Systems offers online and in person training and support.

SensIt (TreePlan Software) is a sensitivity analysis add-in for the Microsoft Excel spreadsheet software. SensIt performs sensitivity analysis on existing Excel-based models. TreePlan provides answers to frequently asked questions for their software.

ServiceModel (ProModel Corporation) is a planning and throughput analysis tool for the service industry. The tool can analyze, visualize, and optimize the layout of a service facility based on performance metrics specified by the user. Users can also pose what-if questions about the layout and its constraints, and the tool will provide options for improving the performance metrics. The tool has import/export capabilities with the Microsoft Excel spreadsheet software. ProModel Corporation provides online and classroom based training programs and provides online support.

SIMULIA (Dassault Systèmes) is a commercial software brand of simulation tools from Dassault Systèmes that includes Abaqus FEA, fe-safe, Isight, Simulation Lifecycle Management, Tosca, and two CATIA environment packages. The CATIA packages, named SIMULIA V5 and SIMULIA V6, provide integrated analysis ca-

pabilities that allow for direct execution from within CATIA. The SIMULIA family of software provides a complete design, analysis, optimization, visualization, and automation environment. Dassault Systèmes offers training courses, documentation, certification courses, and online and phone support.

Smart-Swaps (SAL, Aalto University) is a method and tool to reduce the number of criteria and alternatives for evaluation. The method is based on the book by Hammond et al.[6] The University provides limited help and limited documentation on their web pages. Their web pages are confusing, have poor documentation, and it is unclear how it fits into a larger suite of capabilities. Smart-Swaps is a part of the Decisionarium site for interactive multicriteria decision support tools.

STATISTICA (StatSoft) is a commercial comprehensive statistics and analytics software suite developed by StatSoft. It operates on the Microsoft Windows operating system and is available in web-based and desktop form. StatSoft is a direct competitor to the SAS's Analytics as it provides similar capabilities in data mining, predictive modeling, statistical analysis, and data visualization. STATISTICA can be extended through VBA scripting and integration with programs coded in R language. StatSoft offers online support and training along with free to access videos and tutorials.

System Capabilities Analytic Process (SCAP) (ARL Survivability/Lethality Analysis Directorate [SLAD]) is a method that maps the relationship between components of a system and the system's capabilities, creating what is called the functional skeleton (FS). The FS will depict what system capabilities are functional and which system components are critical to the system's primary goals. This allows for recognition of loss of mission tasks or system capabilities when components of a system fail.

Systems Platform for Integrated Design in Realtime (SPIDR) (University of Southern California) is a tool/method developed by the Institute for Systems Integration at the University of Southern California. SPIDR is programmed in a variant of C. SPIDR is an artificial intelligence based search and optimization engine, also called a "constraint-based design synthesis engine". SPIDR can automatically select from a set of existing components, each with an array of attributes, to build the most preferred system for meeting decision maker preferences for values of mission

[6] Hammond JS, Keeney RL, Raiffa H. Smart choices: a practical guide to making better decisions. Boston (MA): Harvard Business Review Press; 1998.

metrics. SPIDR can generate multiple designs, which are then modeled, analyzed, and simulated to document performance capabilities. There is an optimization algorithm, however details of this algorithm are unknown. The user builds XML-based hierarchies within SPIDR that are called upon during optimization. Limited details are available on how optimization is accomplished, and what the output data looks like (or is explored).

Systems Analysis and Experimentation (SAE) (MITRE) is a framework for executing simulation, optimization, analysis, and visualization commensurate with the time frame and confidence level requested by a sponsor. Within this framework, there are several visualization tools of interest, including SpiderView and ChartBuilder, which enable continuous and immersive data analysis and visualization. The entire systems engineering framework has been under development for some time by MITRE and portions have been applied to real-world scenarios. The types of tools within the SAE set include visualization, decision analysis, and M&S, so it is difficult to categorize this toolset within a single tradespace exploration function.

Tableau (Tableau Software) is a data visualization tool, primarily used by the business intelligence community. With user-provided data, Tableau can generate innovative, visually striking plots. Recently Tableau has added the ability to interface with R, such that users can perform all of their statistical data analysis with R and then open that data in Tableau for visualization. Tableau Software offers training, white papers, blogs, and online tutorials.

Technology Identification, Evaluation, and Selection (TIES) (Georgia Institute of Technology) is a method for assessing trade-off impact of technologies without time-consuming mathematical formulations. Technically feasible solutions are identified with accuracy and speed to reduce design cycle time and costs through the use of DOE and probabilistic methods such as RSEs and Monte Carlo simulation. In this sequential step method the design space is defined, systems are modeled and simulated, and solutions are analyzed and their sensitivities to technologies are assessed. Through the use of JMP, several data visualizations are used to aid the decision maker in technology selection.

Tradespace Analysis for Capabilities, Effectiveness, and Resources (TRACER) (Logistics Management Institute) is a process for linking design parameters with effectiveness metrics and cost. In this way, a user can change inputs to determine the cost and performance, or set the cost and performance to determine the design parameter settings to achieve them. TRACER attempts to optimize within and across decision-making levels, from system design and optimization (What is the best design?), through concept analysis and selection (Which solution approach is best for a mission?), and to mission, strategy, and force assessment (What is the best portfolio?). TRACER depends on cost and effectiveness models linked to design parameters, with weighted sums determining the preferred course of action. There are no publications or references available since the initial 2007 National Defense Industrial Association presentation (http://www.dtic.mil/ndia/2007test/Belcher_SessionD1.pdf), and inquiries to the presenters have gone unanswered.

TreeNet (Salford Systems) is a commercial data mining tool. Its strength is the capability to regress models by generating "trees" that represent changes in response given known impacts to the response by changes in other variables. TreeNet can assess the strength of classification, binary, and multiclass problems using statistical analysis. Salford Systems offers online and in person training and support.

TreePlan (TreePlan Software) is a decision tree add-in for the Microsoft Excel spreadsheet software. TreePlan calculates values of each decision tree branch using existing Excel-based models. TreePlan provides answers to frequently asked questions for their software.

TreePlan ToolKit (TreePlan Software) is the bundle of all 3 TreePlan Software add-ins for the Microsoft Excel spreadsheet software: TreePlan, SensIt, and RiskSim. TreePlan provides answers to frequently asked questions for their software.

VisLab (Massachusetts Institute of Technology [MIT]) is an internally developed research testbed for analysis techniques and visualizations. VisLab is MATLAB-based, possibly similar in nature to Georgia Tech's Rave. The tool and accompanying process were developed at MIT.

Visual Design & Optimization Control (VisualDOC) (Vanderplaats R&D, Inc.) is a general purpose multidisciplinary design, optimization, and process integration software. Analysis modules can be added to it (DOE, LS-DYNA, finite element analysis (FEA), CFD). VisualDOC can output data in parallel plots and 2-D/3-D

scatterplots. The layout of VisualDOC is similar to ModelCenter, where the user can create a flowchart of inputs, outputs, and components, and link codes together (primarily for export to Microsoft Excel spreadsheet software and MATLAB, but also to external tools using wrappers). VisualDOC allows for automation of the design and optimization process. Built-in components include optimization, DOE, response surface methodology, and probabilistic analysis. Vanderplaats offers seminars, workshops, technical support, and training.

Web-HIPRE (SAL, Aalto University) is a web-based decision support tool based on multi-attribute value theory weighting techniques and analytic hierarchy process. This is a web version of the HIPRE 3+ decision analysis software. The University provides limited help and limited documentation on their web pages. Their web pages are confusing, have poor documentation, and it is unclear how it fits into a larger suite of capabilities. Web-HIPRE is a part of the Decisionarium site for interactive multicriteria decision support tools.

Whole System Trades Analysis Tool (WSTAT) (Program Executive Office Ground Combat Systems (PEO-GCS) and Sandia National Laboratories) is the Java version of AAMODAT. AAMODAT was provided by PEO-GCS to Sandia Labs to be enhanced for inclusion with CPAT as a system-level optimization tool. The WSTAT executable is government-owned, but the source code rights belong to Sandia. Output from WSTAT is intended to feed into CPAT. In this way, WSTAT optimizes a system across 5 dimensions (unit cost, O&S cost, performance, growth, and risk) and CPAT optimizes a portfolio across performance, schedule, and cost. WSTAT is intended for use at the program manager level, whereas CPAT is intended for use at the Program Executive Office level.[7]

WSTAT is essentially identical to AAMODAT—requirements getting mapped to the functional objectives, the functional objectives getting mapped to the physical architecture, technology options affecting system metrics (which trace back to the physical architecture), value functions describing stakeholder value over the range of possible metric measures, and priority weightings describing the importance of the metric to the stakeholder. The outputs can be visualized in scatterplot, spider chart, tornado plot, and histogram formats. In this way, depending upon the priority weighting of the system functions, the appropriate subsystems are combined

[7] Edwards S. Capability portfolio analysis tool (CPAT) & whole system trade analysis (WSTA). Paper presented at: Army Systems Engineering Forum (ASEF). 2013 Feb 27; Arlington, VA.

to provide the highest value to the stakeholder. There are a few drawbacks to the WSTAT tool, in that multiobjective optimization, multiattribute utility, uncertainty, and sensitivities are not addressed.

Appendix B. TSE Tool Keep/Reject Rationale

This appendix appears in its original form, without editorial change.

TSE Tool	Developer	Keep/ Reject	Now/ Follow-On	Rationale for Keep / Reject
@RISK	Palisade Corporation	Reject	Neither	Included in DecisionTools Suite 6.0.
1000Minds	1000Minds Ltd	Reject	Neither	Web site is no longer available. No other detailed information available.
AAMODAT	RDECOM-ARDEC	Keep	Now	Development continues within DoD for TSE. Capability has been spun off into WSTAT, which is now packaged with CPAT.
AgenaRisk	Agena Limited	Keep	Follow-on	Performs risk assessment, probabilistics, sensitivity analysis, and visualization to solve complex risk problems. Further investigation needed for follow-on assessment to determine depth of applicability to TSE.
Analytica	Lumina Decision Systems	Keep	Follow-on	Similar in practice to Excel, but establishes systems of equations in a visual (flowchart) style. Capable of uncertainty assessment and probabilistic analysis. Insufficient knowledge of the tool for consideration in current effort.
Analytics	SAS	Keep	Follow-on	Suite of integrated statistical analysis tools. This is the entire SAS tool portfolio. Needs more time for further assessment.
ASEC	RDECOM-TARDEC	Keep	Now	Continued development within DoD for TSE. Web-based, government-developed framework. Decision-centered framework for assessing risk, requirements, and capabilities from a system functional perspective.
ATSV	Penn State ARL	Keep	Now	Continued development within DoD for TSE. Multi-dimensional visualization tool.
Berkeley Madonna	University of California at Berkeley	Reject	Neither	A differential equation solver. Provides a specific, limited application.
CART	Salford Systems	Reject	Neither	Classification and regression decision tree tool; a part of the Salford Predictive Modeler suite.
ClearPoint Strategy	Ascendant Strategy Management Group	Reject	Neither	A strategy management tool. Maps strategic objectives and measures to corporate activities. Not applicable to TSE.
Comparion Suite	Expert Choice, Inc.	Reject	Neither	Limited information from developer. Strictly performs portfolio and organizational decision analysis. Not applicable to TSE.
CPAT	PEO-GCS	Keep	Now	Continued development within DoD for TSE. Portfolio analysis tool.
CyDesign Studio	CyDesign Labs	Keep	Follow-on	Similar in layout to FACT. A model-based systems engineering tool that looks at complex systems holistically. Insufficient knowledge of the tool for consideration in current effort.
D3	D3JS.org	Reject	Neither	Specific to visualization. Relies on external data tables. Enhances TSE tools, but is not itself a TSE tool.
DAKOTA	Sandia National Labs	Keep	Follow-on	Object-oriented framework for design optimization, parameter estimation, uncertainty quantification, and sensitivity analysis. Need to assess in depth in a follow-on effort.
DEA SolverPro	SAITECH, inc.	Reject	Neither	Data envelopment analysis; Limited documentation from website. Not applicable to TSE.
DecideIT	Preference	Keep	Follow-on	Decision analysis tool that can handle imprecision and uncertainty. Insufficient knowledge of the tool for consideration in current effort.
Decision Explorer	Banxia Software Ltd	Reject	Neither	Helps capture thoughts and ideas in detail (like sticky notes). Limited applicability to TSE.

TSE Tool	Developer	Keep/ Reject	Now/ Follow-On	Rationale for Keep / Reject
DecisionTools Suite 6.0	Palisade Corporation	Keep	Follow-on	Excel add-on that conducts risk analysis under uncertainty, statistical analysis, and data visualization. Further investigation needed for follow-on.
D-Sight Desktop	D-Sight	Keep	Follow-on	Provides a framework for multi-stakeholder, multi-criteria decision analysis. Follows a structured decision analysis process. Has data visualization capabilities, but looks to be mainly focused on capturing value and developing utility functions. Insufficient knowledge of the tool for consideration in current effort.
Enterprise Portfolio Simulator	ProModel Corporation	Reject	Neither	High-level strategic planning, project and portfolio management tool. A collaborative and web-based version of Portfolio Simulator.
Equity3	Catalyze Ltd	Reject	Neither	Similar to the Hiview3 product, but with specific application to portfolio management decisions.
Eureqa Desktop	Nutonian, Inc.	Reject	Neither	Capability resides in larger decision analysis or numerical analysis tools already under consideration. However, the tool is free to download and use.
Excel	Microsoft	Keep	Now	Most common visualization and analysis tool. Ubiquitous.
ExtendSim Suite	Imagine That, Inc.	Keep	Follow-on	Model-based simulation tool for continuous and discrete processes. Visualization and statistical analysis features are included. Insufficient knowledge of the tool for consideration in current effort.
FACT	GTRI	Keep	Now	Continued development within DoD for TSE.
ForeTell	DecisionPath, Inc.	Reject	Neither	Project and portfolio management tool that has some analytic and data analysis capability. Not applicable to TSE for engineered systems.
GoldSim Pro	GoldSim Technology Group	Reject	Neither	Although apparently more capable at modeling discrete and continuous processes than competing tools (@RISK, Crystal Ball, Risk Solver) GoldSim is essentially a discrete event simulator and probabilistic simulation add-in for Microsoft Excel. Limited application as a probabilistic simulation add-in.
gPROMS	Process Systems Enterprise Limited	Keep	Follow-on	High-fidelity predictive model-based engineering and optimization software for process industries. Appears able to create custom physics-based models with ability to simulate. Insufficient knowledge of the tool for consideration in current effort.
GRIPS	The Aerospace Corp	Keep	Follow-on	Decision-support process that uses high-dimensional visualization to solve complex problems. Limited documentation available. Insufficient knowledge of the tool for consideration in current effort.
Hiview3	Catalyze Ltd	Reject	Neither	Limited to decision analysis on multi-stakeholder input. Traditional decision analysis where alternatives are scored against criteria and are ranked based on user values. Appears similar to the web-based Decision Lens collaborative tool.
Iris	Ayasdi	Reject	Neither	Looks at relationships amongst variables in data. The visual aspect is what makes this an enticing TSE tool, although may not be applicable to the entire TSE process.
Isight	Dassault Systems	Keep	Follow-on	Similar to ModelCenter. Insufficient knowledge of the tool for consideration in current effort.
JIAT	ODASA-CE	Reject	Neither	Tool is specifically used to build up cost estimates and is not applicable to TSE.
JMP	SAS	Keep	Now	Statistics with interactive graphics; excels at visualization, surrogate modeling, and statistical analysis.

TSE Tool	Developer	Keep/ Reject	Now/ Follow-On	Rationale for Keep / Reject
KNITRO optimization solver	Ziena Optimization LLC	Reject	Neither	Limited application as a non-linear optimization solver.
Logical Decisions for Windows	Logical Decisions	Reject	Neither	Similar logical analysis process as AAMODAT, but does not rank or optimize. Part of the Logical Decisions Portfolio product. A decision analysis product but marketed as a portfolio management product.
Logical Decisions Portfolio	Logical Decisions	Keep	Follow-on	Based on the Logical Decisions for Windows product. Implements optimization and selection of multiple alternatives based on constraints. A decision analysis product but marketed as a portfolio management product. Insufficient knowledge of the tool for consideration in current effort.
MapleSim	Maplesoft	Keep	Follow-on	Similar to Simulink. Built from the open source Modelica library. Insufficient knowledge of the tool for consideration in current effort.
MARS	Salford Systems	Reject	Neither	Limited application as a regression tool. Part of the Salford Predictive Modeler suite.
Mathematica	Wolfram	Keep	Follow-on	Widely used computational environment used for modeling, analyses, programming, and visualization. Further investigation needed for follow-on.
Matlab	Mathworks	Keep	Now	Common numerical analysis tool, large user community, currently in use by ERS Demo team; ARL familiarity
MedModel Optimization Suite	ProModel Corporation	Reject	Neither	Limited application to medical facility modeling, planning, and evaluation.
modeFRONTIER	Esteco	Keep	Follow-on	Multidisciplinary analysis and optimization tool used to link outside analysis tools and provide some statistical analysis and post processing. Similar to ModelCenter. Insufficient knowledge of the tool for consideration in current effort.
ModelCenter	Phoenix Integration	Keep	Now	Common MDAO tool, moderately sized user community, currently in use by ERS Demo team.
Nexus	iChrome Ltd.	Keep	Follow-on	Similar functionality and scope as ModelCenter and modeFRONTIER. Insufficient knowledge of the tool for consideration in current effort.
OpenMDAO	NASA	Keep	Now	Free, open source MDAO tool developed by NASA Glenn. Gaining popularity in government research community.
OptiY	OptiY GmbH	Keep	Follow-on	Similar to ModelCenter but may have more statistical functionality. Insufficient knowledge of the tool for consideration in current effort.
Portfolio Simulator	ProModel Corporation	Reject	Neither	Not a TSE tool, strictly looking at portfolio optimization
Process Simulator	ProModel Corporation	Reject	Neither	MS Visio plug-in for process analysis and optimization; not standalone tool, other software required for use.
Project Simulator	ProModel Corporation	Reject	Neither	MS Project plug-in for schedule analysis and optimization; not standalone tool, other software required for use.
Promax Professional	Cogentus Consulting Limited	Keep	Follow-on	Aids in conducting a detailed decision analysis process. Insufficient knowledge of the tool for consideration in current effort.
ProModel Optimization Suite	ProModel Corporation	Reject	Neither	Modeling of continuous processes for optimization of planning, warehousing, and logistics.
R	R Foundation	Keep	Now	Widely used statistical analysis focused programming language. Top in Rexer surveys.

TSE Tool	Developer	Keep/ Reject	Now/ Follow-On	Rationale for Keep / Reject
RandomForests	Salford Systems	Reject	Neither	Decision tree tool; a part of the Salford Predictive Modeler suite.
Rave	Georgia Institute of Technology	Keep	Follow-on	Freeware TSE tool developed in Matlab (a commonly used tool). Similar functionality to JMP. Further investigation needed for follow-on.
RICH Decisions	Systems Analysis Laboratory, School of Science, Aalto University	Reject	Neither	An alternative ranking and preference modeling tool that is included in the web-based RPM-Decisions tool. Confusing web page, poor documentation, and unclear how it fits into a larger suite of capabilities.
Risk Solver Pro	Frontline Systems, Inc.	Reject	Neither	Excel add-in for performing probabilistic Monte Carlo simulation on Excel-based models. Similar in functionality to GoldSim. Limited application as a probabilistic simulation add-in.
RiskSim	TreePlan Software	Reject	Neither	Included in TreePlan ToolKit. An MS Excel add-in for Monte Carlo simulations for Excel based models, random number generator, and plotter.
ROSETTA	Georgia Institute of Technology	Reject	Neither	Limited application to capturing stakeholder value. Although the tool has a novel approach to mapping stakeholder needs to value, it is not in itself a TSE tool. Could be useful as part of a piecemeal TSE environment.
RPM-Decisions	Systems Analysis Laboratory, School of Science, Aalto University	Keep	Follow-on	A Java software tool that performs portfolio modeling and optimization using MCDA. However, could be implemented to perform analysis of alternative designs within a tradespace. Confusing web page, poor documentation, and unclear how it fits into a larger suite of capabilities. Insufficient knowledge of the tool for consideration in current effort.
SAE	MITRE	Keep	Follow-on	A wide ranging set of systems engineering tools, including visualization, M&S, and decision analysis. Insufficient knowledge of the tool for consideration in current effort.
Salford Predictive Modeler	Salford Systems	Keep	Follow-on	This is the suite which contains the other four Salford decision tree and regression products: CART, TreeNet, MARS, and RandomForests. Further investigation needed for follow-on.
SCAP	RDECOM-ARL-SLAD	Keep	Follow-on	A government-developed and owned tool. Can be used to assess interaction between subsystems and components and the whole system's cost or performance. Limited documentation and use cases, but worthy of a follow-on analysis given the model-based structure and government ownership.
SensIt	TreePlan Software	Reject	Neither	Included in TreePlan ToolKit. An MS Excel add-in for performing a sensitivity analysis.
ServiceModel Optimization Suite	ProModel Corporation	Reject	Neither	Specific to the service industry, specifically looking at throughput analysis.
SIMULIA	Dassault Systemes	Reject	Neither	Specific to CAD models and FEA. Not applicable to TSE.
Smart-Swaps	Systems Analysis Laboratory, School of Science, Aalto University	Reject	Neither	A method and tool to reduce the number of criteria and alternatives for evaluation. Confusing web page, poor documentation, and unclear how it fits into a larger suite of capabilities.

TSE Tool	Developer	Keep/ Reject	Now/ Follow-On	Rationale for Keep / Reject
SPIDR	University of Southern California	Keep	Follow-on	A tool/method that uses AI-driven search and optimization. Uses XML-based system hierarchies to allocate components in order to meet user objectives. Limited documentation and use cases, but worthy of a follow-on analysis given that it is marketed as a TSE tool.
STATISTICA	StatSoft	Keep	Follow-on	High percentage of users from Rexer survey and high user satisfaction. Similar in role to SAS. Further investigation needed for follow-on.
Tableau	Tableau Software	Keep	Follow-on	Data mining and visualization tool. Ease of use, customizable dashboards. Insufficient knowledge of the tool for consideration in current effort.
TIES	Georgia Institute of Technology	Keep	Now	The techniques used within the method, and the method overall, is directly applicable to TSE. A structured process for assessing the impact of adding technologies to systems, which can be compared with FACT.
TRACER	LMI Consulting	Reject	Neither	Limited publications; no apparent usage since initial NDIA 2007 presentation.
TreeNet	Salford Systems	Reject	Neither	Decision tree tool; a part of the Salford Predictive Modeler suite.
TreePlan	TreePlan Software	Reject	Neither	Included in TreePlan ToolKit; MS Excel add-in for creating decision trees.
TreePlan ToolKit	TreePlan Software	Keep	Follow-on	Toolkit which includes a decision tree designer, sensitivity assessment tool, and Monte Carlo simulation tool. For use with Excel based models. Further investigation needed for follow-on; website is relatively non-descriptive, and it appears that these tools have focused and limited functionality.
VisLab	MIT	Keep	Follow-on	Use currently limited to internal MIT. Enables preference-driven TSE. Limited documentation and use cases, but worthy of a follow-on analysis.
VisualDOC	Vanderplaats R&D, Inc.	Keep	Follow-on	Similar to ModelCenter. Performs DOE, RSM, and probabilistics. Covers several aspects of TSE processes. Insufficient knowledge of the tool for consideration in current effort.
Web-HIPRE	Systems Analysis Laboratory, School of Science, Aalto University	Reject	Neither	A web-based value tree and AHP decision support tool. Confusing web page, poor documentation, and unclear how it fits into a larger suite of capabilities.
WSTAT	PEO-GCS	Keep	Now	Continued development within DoD for TSE.

Appendix C. TSE Tool Attribute Definition and Rationale

This appendix appears in its original form, without editorial change.

	Attribute	Definition	Rationale for Inclusion	Primary Origin
Class	Tool	A piece of software, proprietary or commercial, to conduct tradespace exploration, analysis, and/or data visualization.	Users need to differentiate between the application of a tool and a process. There will be cases where the tool is embedded within a process.	ARL
	Process	An analysis method or workflow for conducting tradespace exploration, analysis, and/or data visualization.	Users need to differentiate between the application of a tool and a process. There will be cases where the tool is embedded within a process.	ARL
Usage	Specific industries or market segments in which the software tool is more popular	Are there sectors of industry that routinely use the tool most often?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Specific applications in which the software tool is more widely used for	What is the specific task or application that the tool is used for most often?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	User or developer community size	How large and mature is the community who develops, uses, supports, and advances this tool?	It is important to know if the developer community is small or large, or if it is growing or shrinking. Want to avoid investing in the current "best thing" and instead place investments on tools that are on the upswing.	2011 Rexer Data Miner Survey
Operating Systems	Windows	Does the tool operate in Windows operating system?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Mac OS	Does the tool operate in Macintosh operating system?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Unix/Linux	Does the tool operate in Unix or Linux operating systems?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Flavors of Unix/Linux	Which versions of Unix or Linux operating systems can the tool operate in?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Web implementation	Can the tool be implemented or used from the open web (e.g., http or https)?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Other Operating Systems	Can the tool operate in operating systems not listed above?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
Pricing Information	Commercial	What is the purchase price of the standard commercial version of the tool/process?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Education	What is the purchase price of the education version of the tool/process?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Enhanced/High Performance	What is the purchase price of the enhanced or higher performance (i.e., 'deluxe') version of the tool/process?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey

	Attribute	Definition	Rationale for Inclusion	Primary Origin
	Open/Free	Is the tool/process considered Open Source or Freeware software; available without cost to anyone, public or government?	There is a growing interest in tools that are open source, as well as tools that are free/limited in capability.	ARL
Training Classes Offered	Vendor	Does the vendor offer training classes for the tool/process?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	3rd Party	Does a third party organization offer training classes for the tool/process?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Classroom	Are in-classroom training sessions offered by the vendor or a third party?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Online	Are online training sessions offered by the vendor or a third party?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
Training/Experience Needed	Basic	Requires little to no prior knowledge of the software interface or underlying math to effectively use and generate results. Operation is intuitive and the user can learn how to use it with relative ease.	A cursory level of competency proficiency needs to be assigned. Users need to have an understanding of the expected relative level of capability required to effectively use, and potentially improve, the tool/process. The basic, intermediate, and advanced levels should be enough to inform the user of the amount of training and experience needed to conduct TSE using the tool.	ARL
	Intermediate	Requires prior intermediate level knowledge or of the subject matter to effectively use the tool, generate and interpret results. Minimal training may be needed.	A cursory level of competency proficiency needs to be assigned. Users need to have an understanding of the expected relative level of capability required to effectively use, and potentially improve, the tool/process. The basic, intermediate, and advanced levels should be enough to inform the user of the amount of training and experience needed to conduct TSE using the tool.	ARL

	Attribute	Definition	Rationale for Inclusion	Primary Origin
	Advanced	Requires prior advanced level knowledge of the subject matter to effectively use the tool, generate and interpret results. Extensive training (possibly in the form of developer taught classes) may be required to take full advantage of all capabilities.	A cursory level of competency proficiency needs to be assigned. Users need to have an understanding of the expected relative level of capability required to effectively use, and potentially improve, the tool/process. The basic, intermediate, and advanced levels should be enough to inform the user of the amount of training and experience needed to conduct TSE using the tool.	ARL
Software Attributes	Is live or delayed response help available from the developer or broader user community	Can the user reach out to a live person for advice or help, or is there a user forum that offers delayed responses to questions?	Beyond help menus, demos, or tutorials, there is a need to obtain live or delayed responses to questions, inquiries, issues, etc., as well as learn from others.	2011 Rexer Data Miner Survey
	Are help menu, demos, or tutorials available	Is there help available within the tool, and are there demo videos or tutorials that can aid in learning how to better and more fully use the tool?	Users need the ability to find answers to frequently asked questions, or receive help in executing a feature of the tool.	2011 Rexer Data Miner Survey
	Limitations on the dataset capable of being explored	Are there size (i.e., memory, row, column, etc.) limitations to the tool's capability?	Although this question was dropped from the 2010 OR/MS Today DAS survey, this is a concern for ERS. There is a need to understand any limitations of the tool in terms of how much data it can analyze, plot, store, etc.	Sponsor
	Approved for use on a classified network	Is the tool approved for use on a classified network?	Not only need to know if the tools is approved for use on a classified network, but there is also a need to know what, if anything, is preventing its use as such (e.g., module or algorithm written by non-US).	Sponsor
	Currently in use by any of the ERS Demonstration Project teams	Is the tool currently in use by any of the ERS Demonstration Project teams?	Desire to know if the tool is in use, or planned for future use, by any of the ERS Demonstration Project teams.	Sponsor
	Limitations in "free" software (e.g., toolbox is free but host software is not).	Are there any limitations or caveats to this tool being "free"?	The tool may be "free" for download and use, but does it require a costly parent tool (e.g., Matlab required to run a specific tool box).	Sponsor

	Attribute	Definition	Rationale for Inclusion	Primary Origin
	Standard or open data storage, interchange, and reuse	Does the tool support standard file formats for data storage, transfer, and reuse?	Non-standard or proprietary data formats inhibit linking codes and performing multi-disciplinary analysis and optimization.	ERS Tradespace Workshop
	Primary Language to Expand or Develop Functionality	What programming language allows expansion of the tool's capabilities? Include languages that impact the native tool, shared toolboxes, and add-ins.	Knowing the programming language will help assess required user proficiency level, compatibility with other tools, and especially how more, or custom, capabilities can be added. Examples include Excel, Matlab, and R.	ARL
Applications	Best option using multiple objectives	Can the tool select a best option from a list of existing options using multiple, competing objectives?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Representation / analysis of uncertainty	Can the tool represent uncertainty or perform analysis of the uncertainty within the model results?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Representation / analysis of probabilistic dependencies	Can the tool represent probabilistic dependencies or perform analysis of the dependencies between inputs and outputs?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Risk Preference	Can the tool model risk preference of individual stakeholders, or of a group?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Sequential decision making	Does the tool conduct sequential decision making?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Portfolio decision making	Does the tool conduct portfolio decision making, including project/process portfolio management and simulation?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Bayesian Belief Networks	Can the tool create and/or use Bayesian belief networks?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Multiple stakeholders collaboration	Can the tool handle inputs from multiple stakeholders, either through combining, normalizing, utility functions, or preferences?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
Software Features	Interfaces to other software:	Can the tool interface with other software, either manually or automatically, via import or export of inputs/outputs?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Import (database, spreadsheet)	Can the tool import databases? Spreadsheets?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Export (presentation graphics)	Can the tool export presentation graphics, such as charts and figures?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Export (model to MS Excel)	Can the tool export underlying models to MS Excel?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	XML	Can the tool handle XML inputs and/or produce XML outputs	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	API (Embedded Decision Support)	Does the tool have an Application Programming Interface (API; specifies how software components interact with each other) so that the tool's functionality can be embedded into	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey

	Attribute	Definition	Rationale for Inclusion	Primary Origin
		other applications?		
	Limited use (Run-time) version for those without the software?	Is a run-time version of the tool available so that others without the tool can run models that were generated by the tool?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can model structure be copied?	Can the user copy and paste parts of the model structure to limit the amount of repetition in model creation?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can model segments be moved easily within the model?	Can the user cut and paste parts of the model structure to limit the amount of repetition in model creation?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can model structure be displayed on screen?	Can the model structure be displayed graphically for the user to inspect and understand ordered flow of information?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can model structure be printed?	Can selected portions of the model be printed?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can user protect data from other users?	Can the user set permissions such that certain data or fields within the tool are protected/hidden from other users?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can user protect model structure and formulae?	Can the user set permissions such that certain model structures or formulae within the tool are protected/hidden from other users?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Does the software support explicitly group elicitation?	Does the tool contain separate features or fields for group elicitation (versus single input)?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	If yes, will it support decentralized elicitation?	If the tool explicitly supports group elicitation, does it support decentralized elicitation where multiple users may be geographically separated?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	If yes, will it support simultaneous data input?	If the tool supports decentralized elicitation from multiple, geographically separated users, does it support simultaneous data input from the users?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	If yes, does it support simultaneous viewing?	If the tool supports simultaneous data input from multiple, distributed users, does it support simultaneous, real-time viewing of the tool canvas or data entry fields?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	If yes, is a record of model evolution kept?	If the tool supports simultaneous, distributed data input and viewing, does it keep a record of model evolution?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Capture descriptive comments or narrative during TSE.	Does the tool allow capture of written/typed or verbal comments during data entry and subsequent viewing of the effect of changing inputs?	There is a need to document the decisions that are being made throughout the TSE process. Analysts and decision makers may "see" something from a unique	ERS Tradespace Workshop

	Attribute	Definition	Rationale for Inclusion	Primary Origin
			perspective that is not intuitive to others. They may want to capture written or verbal comments to explain the effect that they saw when changing an input or condition.	
	Record TSE actions for playback or re-creation of the exploration.	Does the tool allow the user to record TSE actions for the purposes of rewinding and playing back (i.e., instant replay) as well as rewinding, playing back, and entering into the process to take a new TSE path?	TSE exploration is performed differently by different people. There are multiple purposes for recording and then playing back the actions of TSE: documenting the origin of a decision, documenting good TSE practice for inclusion in a "TSE playbook", learning decision maker patterns and intent, etc. There is also a desire to track and visualize how the tradespace expands, reduces, or repopulates over time as decisions are made or as new information becomes available during the TSE process.	ERS Tradespace Workshop
	Automatically repopulate the TS based on user-selected seed points.	Can the user "click" within or "point" to a region in the tradespace and set this point as a seed from which the tool can further fill in or re-populate the tradespace?	The human tradespace explorer desires an ability to fill in or re-populate regions of the tradespace that are "interesting", sparse, overpopulated, or questionable.	ERS Tradespace Workshop
	Create predictive models using multiple techniques (e.g., regression, Kriging, neural nets, etc.).	Can the tool create surrogate models of data such that the data can be replaced with equations?	There is a need to generate relationships within and amongst data in the tradespace such that users can quickly re-populate regions of the tradespace or explore new regions. Replacing data with an equation, or set of equations, also enables near real-time interaction with data and dynamic analyses.	Literature Review
	Access external databases in real-time to supplement internal data.	Can the tool link, or connect, to external databases in order to supplement static data sets within the tool?	TSE tools include the ability to visualize datasets, but also require the need to link to datasets that have already been populated by others but that may not reside locally.	ERS Tradespace Workshop

	Attribute	Definition	Rationale for Inclusion	Primary Origin
	Access to cost models, databases, or estimating relationships?	Can the tool link to, or plug in to, cost estimating resources?	As opposed to assessing the lifecycle cost of a design after it has been chosen based on performance metrics, ERS desires to include this information as part of the decision making and TSE process. This category starts with cost but is expected to expand to include "ilities" such as safety, reliability, and sustainability.	Sponsor
	Express alternate use cases and operational scenarios.	Can the user generate alternate use cases and operational scenarios to compare to the baseline?	Alternate user scenarios and future operational environments must be expressed in sufficient detail to support decision making in the TSE process. Capturing this information will help better understand which scenarios are driving overall development and cost risk. Also, these "alternate futures" will enable assessment of system resiliency and robustness.	ERS Tradespace Workshop
	Graphical and quantitative assessment of technology readiness, technology maturity, and technology integration levels	Can the tool graphically and quantitatively express technology readiness, maturity, and integration levels?	Programs are driven to using lower risk (high maturity and readiness) technologies. Technology development risk, lifecycle cost, and other performance characteristics must be sufficiently traded in order to make informed decisions on product development.	ERS Tradespace Workshop
	Near real-time queries	Does the tool allow user interaction for scenarios, storylines, and other "what-ifs" that might aid the decision maker and analyst in exploration of impacts due to constraints, assumptions, and technology insertion?	Users need the ability to interact with the tradespace by performing near real-time queries based on observations and new knowledge.	ERS Tradespace Workshop
	Customized data layout	Can the tool create a customized layout of qualitative and quantitative graphics and data?	Decision makers want the ability to customize graphic layouts based on their particular perspective of the system (e.g., performance tradeoffs, material tradeoffs, and lifecycle cost tradeoffs).	ERS Tradespace Workshop

	Attribute	Definition	Rationale for Inclusion	Primary Origin
	Graphical decision network	Does the tool allow for mapping or linking decisions from the high-level decision maker metrics (e.g., cost, schedule) down to the low-level design decisions (e.g., material selection, dimensions/tolerances)?	Decision makers are interested in knowing the rationale and recommendations of the design engineers, but ultimately view the "goodness" of a design through a lens that contains only a few high-level metrics. It is anticipated that a graphical decision network will enable deeper understanding of decision impacts.	ERS Tradespace Workshop
	Selective search	Can the user execute searches based on user-specified selective dimensions or user-specified regions of the tradespace?	More effective and efficient search algorithms are required in order to support the multiple dimensions envisioned with ERS tradespaces. Users want the ability to "coach" the search based on human knowledge and/or insight.	ERS Tradespace Workshop
	Generate Data Internally	Can the tool internally generate data from models (as opposed to requiring data sets to be imported from other sources which execute models)?	Executing a model will produce output data. This ability can be used for Monte Carlo simulations and also for populating the tradespace for deeper analysis.	ARL
	Auto-discover relationships within data	Can the tool automatically discover, identify, or reveal relationships within a dataset or across multiple datasets?	The human tradespace explorer may not have the ability to recognize patterns, groupings, or trends simultaneously in multiple dimensions within a dataset. There is a need for automatic recognition or discovery of this information, and then displaying it to the user.	ARL
	Accept real-time user input and steering during the TSE process.	Can the user interject real-time input to the TSE process (i.e., what-ifs from other collaborators)?	There is a need for collaborative TSE. The tool should be able to accept real-time changes or inputs from any one of the users who want to perform a what-if analysis, or if a user wants to create a new branch in the TSE decision tree.	ERS Tradespace Workshop
	Customize the TSE process, analysis, optimization, or visualization through scripting.	Does the tool allow the user to develop their own custom code? For example, multiple JMP analyses can be combined to run in succession within a single JMP script, and VBA can be used to create	There is a need for the tradespace explorer to generate custom analysis, optimization, and visualizations, beyond what	ERS Tradespace Workshop

	Attribute	Definition	Rationale for Inclusion	Primary Origin
		statistical analyses not available natively in Excel or through add-ins.	may be available in the out-of-the-box tool, in order to make more informed decisions.	
Decision Algorithms Implemented	MODA / MAUT	Does the tool use any MODA/MAUT algorithms?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	AHP	Does the tool have built-in capability to perform AHP, including consistency checks?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Other	Does the tool use another decision algorithm other than MODA/MAUT/AHP? If yes, then which ones?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
Availability of graphical elicitation techniques	Model structure / Brainstorming	Does the tool use graphical techniques to elicit requirements, ideas, thoughts, or model structure from the user?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Value functions / scores	Does the tool visually depict value functions to elicit information from the user?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Value weights	Does the tool visually depict value weights to elicit information from the user?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Probabilities	Does the tool visually depict probabilities to elicit information from the user?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Risk preference	Does the tool visually depict risk preference to elicit information from the user?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Swing weight methods	Does the tool implement swing weight methods to graphically elicit information from the user?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can probabilities or weights be defined as variables that can be operated on?	Does the tool allow probabilities or weights to be defined as variables?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can the tool generate strategy tables?	Does the tool generate strategy tables, where multiple options are listed for multiple decision areas?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can the user document structure or judgments with text?	Does the tool allow users to document model structure, assumptions, or other judgments with text?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
Types of output displays and analyses charts	Are graphical sensitivity analyses possible on either weights or probabilities?	Does the tool plot sensitivity analyses on either weights or probabilities?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Can analytical results be portrayed graphically?	Does the tool plot/chart analytical results?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey

	Attribute	Definition	Rationale for Inclusion	Primary Origin
	Can the tool produce Expected Value (EV) Tornado Diagrams?	Does the tool produce EV tornado diagrams, such that the user's attention can be called to variables that have the greatest impact on expected value?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Does the software support two-way sensitivity analysis	Does the tool determine how a combination of any two inputs affects an output?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Does the software determine value of imperfect information?	Does the tool determine value of imperfect information (the amount one would be willing to 'pay' for obtaining additional, uncertain information)?	Legacy OR/MS Today DAS Survey Entry	2012 OR/MS Today DAS Survey
	Select data for plotting and/or analysis through filtering, sorting, selecting, excluding.	Can the user select or exclude data from an analysis or plot?	Data may be inaccurate, incomplete, or not appropriate for a specific analysis. The user needs an ability to perform these actions on the data when conducting analysis or generating visualizations.	Literature Review
	Visualization of data through linked plots (such as small multiples).	If multiple plots are laid out on the viewing canvas, can the tool automatically link the plots such that highlighting a point in one plot results in the corresponding points being highlighted in all other plots?	There is a need to view data in more than 2 dimensions simultaneously. One method is to view multiple 2D plots simultaneously and manually trace a point (design) throughout multiple coordinates.	Literature Review

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Appendix D. Mapping of TSE Tools to Attributes

This appendix appears in its original form, without editorial change.

		Class		Usage			Operating Systems				
Attribute		Tool	Process	Specific industries or market segments in which the software tool is more popular	Specific applications in which the software tool is more widely used for	User or developer community size	Windows	Mac OS	Unix/Linux	Flavors of Unix/Linux	Web implementation
Definition		A piece of software, proprietary or commercial, to conduct tradespace exploration, analysis, and/or data visualization.	An analysis method or workflow for conducting tradespace exploration, analysis, and/or data visualization.	Are there sectors of industry that routinely use the tool most often?	What is the specific task or application that the tool is used for most often?	How large and mature is the community who develops, uses, supports, and advances this tool?	Does the tool operate in Windows operating system?	Does the tool operate in Macintosh operating system?	Does the tool operate in Unix or Linux operating systems?	Which versions of Unix or Linux operating systems can the tool operate in?	Can the tool be implemented or used from the open web (e.g., http or https)?
Tool/Process	**Developer**	1	2	3	4	5	6	7	8	9	10
AAMODAT	RDECOM-ARDEC	Y	Y	Military AoA's	Decision analysis for analysis of alternatives using VFT	Small	Y	?	?		N
ASEC	RDECOM-TARDEC	Y	Y	Military	Management of risk and opp., decisions, capabilities, and requirements	Small	Y	Y	Y		Y
ATSV	Penn State ARL	Y		Aerospace, automotive, energy	Visual steering, histograms, binned plots, clustering	Small	Y	Y	?		N
CPAT	PEO-GCS	Y		Military	Establish optimum mix of existing vehicles	Small	Y	?	?		N
Excel	Microsoft	Y		Data analysis	Data visualization, plotting, and fitting	Large	Y	Y	Y		N
FACT	GTRI	Y	Y	Military	Model-based ground and amphibious vehicle design	Small	Y	Y	Y		Y
JMP	SAS	Y			Data visualization, surrogate modeling, statistical analysis	Medium	Y	Y	Y	Suse, Redhat, Fedora	N
Matlab	Mathworks	Y			Algorithm development, data analysis, numeric computation	Large	Y	Y	Y		N
ModelCenter	Phoenix Integration	Y		Product Development Teams	Integration and analysis of multiple software and optimization	Large	Y	N	N		N
OpenMDAO	NASA	Y		Engineering	Multidisciplinary Design, Analysis and Optimization	Small	Y	Y	Y	Any with python	N
R	R Foundation	Y		Financials, Media	Statistical analysis and data visualizations	Large	Y	Y	Y	Debian, Redhat, Suse, Ubuntu	N
TIES	Georgia Institute of Technology		Y	Academia, Engineering	Technology Identification, Sensitivity Analysis, Surrogate Modeling	Small	N/A	N/A	N/A	N/A	N/A
WSTAT	PEO-GCS	Y	Y	Military AoA's	Decision analysis for analysis of alternatives using VFT	Small	Y	?	?		N

			Pricing Information				Training Classes Offered				
Attribute		Other Operating Systems	Commercial	Education	Enhanced/High Performance	Open/Free	Vendor	3rd Party	Classroom	Online	Basic
Definition		Can the tool operate in operating systems not listed above?	What is the purchase price of the standard commercial version of the tool/process?	What is the purchase price of the education version of the tool/process?	What is the purchase price of the enhanced or higher performance (i.e., 'deluxe') version of the tool/process?	Is the tool/process considered Open Source or Freeware software; available without cost to anyone, public or government?	Does the vendor offer training classes for the tool/process?	Does a third party organization offer training classes for the tool/process?	Are in-classroom training sessions offered by the vendor or a third party?	Are online training sessions offered by the vendor or a third party?	Requires little to no prior knowledge of the software interface or underlying math to effectively use and generate results. Operation is intuitive and the user can learn how to use it with relative ease.
Tool/Process	**Developer**	11	12	13	14	15	16	17	18	19	20
AAMODAT	RDECOM-ARDEC		N/A	N/A	N/A	Y	N	N	N	N	
ASEC	RDECOM-TARDEC		N/A	N/A	N/A	Y	Y	Y	Y	N/A	
ATSV	Penn State ARL		N/A	N/A	N/A	Y	N	N	N	N	Y
CPAT	PEO-GCS		N/A	N/A	N/A	N/A	N	N	N	N	
Excel	Microsoft		$220	$140	$400	N	Y	Y	Y	Y	Y
FACT	GTRI		N/A	N/A	N/A	Y	Y	N	N	Y	
JMP	SAS	iOS	$1,400	$1,400	$1,400	Y	Y	Y	Y	Y	Y
Matlab	Mathworks	iOS, Android	$2,150	$99	$2,150	N	Y	Y	Y	Y	Y
ModelCenter	Phoenix Integration		~$20,000	?	?	N	Y	Y	Y	Y	Y
OpenMDAO	NASA	N	N/A	N/A	N/A	Open	Y	N	N	Y	
R	R Foundation	N	N/A	N/A	N/A	Open	N/A	Y	Y	Y	
TIES	Georgia Institute of Technology	N/A	N/A	N/A	N/A	Y	Y	N/A	Y	N/A	
WSTAT	PEO-GCS		N/A	N/A	N/A	Y	N	N	N	N	

		Training/Experience Needed		Software Attributes							
Attribute		Intermediate	Advanced	Is live or delayed response help available from the developer or broader user community	Are help menu, demos, or tutorials available	Limitations on the dataset capable of being explored	Approved for use on a classified network	Currently in use by any of the ERS Demonstration Project teams	Limitations in "free" software (e.g., toolbox is free but host software is not).	Standard or open data storage, interchange, and reuse	Primary Language to Expand or Develop Functionality
Definition		Requires prior intermediate level knowledge or of the subject matter to effectively use the tool, generate and interpret results. Minimal training may be needed.	Requires prior advanced level knowledge of the subject matter to effectively use the tool, generate and interpret results. Extensive training (possibly in the form of developer taught classes) may be required to take full advantage of all capabilities.	Can the user reach out to a live person for advice or help, or is there a user forum that offers delayed responses to questions?	Is there help available within the tool, and are there demo videos or tutorials that can aid in learning how to better and more fully use the tool?	Are there size (i.e., memory, row, column, etc.) limitations to the tool's capability?	Is the tool approved for use on a classified network?	Is the tool currently in use by any of the ERS Demonstration Project teams?	Are there any limitations or caveats to this tool being "free"?	Does the tool support standard file formats for data storage, transfer, and reuse?	What programming language allows expansion of the tool's capabilities? Include languages that impact the native tool, shared toolboxes, and add-ins.
Tool/Process	**Developer**	21	22	23	24	25	26	27	28	29	30
AAMODAT	RDECOM-ARDEC	Y		Y	N	Yes; limited by Excel	?	N	N	Y (CSV)	VBA
ASEC	RDECOM-TARDEC	Y		N	N	N	N	N	N	Y (SQL)	HTML
ATSV	Penn State ARL			N	N	Yes; limited by Excel	N	N	N	Y (CSV, TXT)	Java
CPAT	PEO-GCS		Y	N	N	Yes; limited by Excel	?	N	N/A	Y (CSV)	VBA
Excel	Microsoft	Y		Y	Y	Y	Y	Y	Y	Y (CSV, XML)	VBA
FACT	GTRI	Y		Y	Y	?	N	N	N	Y (HTML, XML)	Java, Python
JMP	SAS	Y		Y	Y	Y	?	Y	Y (30 day trial)	Y (CSV, TXT)	JMP Scripting Language
Matlab	Mathworks			Y	Y	?	?	Y	N/A	Y	Matlab
ModelCenter	Phoenix Integration	Y		Y	Y	?	?	Y	N/A	Y	ModelCenter
OpenMDAO	NASA	Y	Y	Y	Y	Limits determined by local machine capabilities	N	N	N	Y	Python
R	R Foundation	Y	Y	Y	Y	Limits determined by local machine capabilities	N	N	N	Y	R
TIES	Georgia Institute of Technology	Y	Y	N	Y	N/A	N/A	N	N/A	N/A	N/A
WSTAT	PEO-GCS	Y		Y	N	Yes; limited by Excel	?	N	N	Y (CSV)	Java

		Applications									
Attribute		Best option using multiple objectives	Representation / analysis of uncertainty	Representation / analysis of probabilistic dependencies	Risk Preference	Sequential decision making	Portfolio decision making	Bayesian Belief Networks	Multiple stakeholders collaboration	Interfaces to other software:	Import (database, spreadsheet)
Definition		Can the tool select a best option from a list of existing options using multiple, competing objectives?	Can the tool represent uncertainty or perform analysis of the uncertainty within the model results?	Can the tool represent probabilistic dependencies or perform analysis of the dependencies between inputs and outputs?	Can the tool model risk preference of individual stakeholders, or of a group?	Does the tool conduct sequential decision making?	Does the tool conduct portfolio decision making, including project/process portfolio management and simulation?	Can the tool create and/or use Bayesian belief networks?	Can the tool handle inputs from multiple stakeholders, either through combining, normalizing, utility functions, or preferences?	Can the tool interface with other software, either manually or automatically, via import or export of inputs/outputs?	Can the tool import databases? Spreadsheets?
Tool/Process	**Developer**	31	32	33	34	35	36	37	38	39	40
AAMODAT	RDECOM-ARDEC	Y	Y	Y	Y	Y	N	N	Y	Y	Y
ASEC	RDECOM-TARDEC	N	Y	N	Y	Y	Y	N	Y	Y	Y
ATSV	Penn State ARL	N	Y	N	N	N	N	N	Y	Y	Y
CPAT	PEO-GCS	Y	Y	N	N	N	Y	N	Y	Y	Y
Excel	Microsoft	Y	Y	Y	Y	N	Y	N	Y	Y	Y
FACT	GTRI	N	Y	Y	N	N	N	N	Y	Y	N
JMP	SAS	N	Y	Y	N	N	N	N	Y	Y	Y
Matlab	Mathworks	N	Y	?	N	N	N	N	Y	Y	Y
ModelCenter	Phoenix Integration	N	Y	Y	N	N	N	N	Y	Y	Y
OpenMDAO	NASA	Y	N	N	N	N	N	Y	Y	Y	Y
R	R Foundation	N	Y	Y	N	N	N	Y	N	Y	Y
TIES	Georgia Institute of Technology	N	N	N	N	N	N	N	N	N	N
WSTAT	PEO-GCS	Y	Y	Y	Y	Y	N	N	Y	Y	Y

Attribute		Export (presentation graphics)	Export (model to MS Excel)	XML	API (Embedded Decision Support)	Limited use (Run-time) version for those without the software?	Can model structure be copied?	Can model segments be moved easily within the model?	Can model structure be displayed on screen?	Can model structure be printed?	Can user protect data from other users?
Definition		Can the tool export presentation graphics, such as charts and figures?	Can the tool export underlying models to MS Excel?	Can the tool handle XML inputs and/or produce XML outputs	Does the tool have an Application Programming Interface (API; specifies how software components interact with each other) so that the tool's functionality can be embedded into other applications?	Is a run-time version of the tool available so that others without the tool can run models that were generated by the tool?	Can the user copy and paste parts of the model structure to limit the amount of repetition in model creation?	Can the user cut and paste parts of the model structure to limit the amount of repetition in model creation?	Can the model structure be displayed graphically for the user to inspect and understand ordered flow of information?	Can selected portions of the model be printed?	Can the user set permissions such that certain data or fields within the tool are protected/hidden from other users?
Tool/Process	**Developer**	41	42	43	44	45	46	47	48	49	50
AAMODAT	RDECOM-ARDEC	Y	Y	Y	N	N/A	N	N	Y	Y	N
ASEC	RDECOM-TARDEC	Y	N	?	Y	N/A	Y	Y	Y	Y	N
ATSV	Penn State ARL	Y	Y	N	N	N/A	N/A	N/A	N/A	N/A	N
CPAT	PEO-GCS	Y	Y	?	N	N/A	N	N	Y	?	?
Excel	Microsoft	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
FACT	GTRI	Y	N	Y	N	Y	Y	Y	Y	Y	Y
JMP	SAS	Y	Y	Y	Y	N	Y	Y	Y	Y	?
Matlab	Mathworks	Y	Y	Y	Y	Y	Y	Y	Y	Y	?
ModelCenter	Phoenix Integration	Y	Y	Y	Y	N	Y	Y	Y	Y	?
OpenMDAO	NASA	Y	N	N	N	N	N	Y	Y	Y	N
R	R Foundation	Y	N	Y	Y	N	Y	Y	N	N	?
TIES	Georgia Institute of Technology	N	N	N	N	N	N	N	N	N	N
WSTAT	PEO-GCS	Y	Y	Y	N	N/A	N	N	Y	Y	N

		Software Features									
Attribute		Can user protect model structure and formulae?	Does the software support explicitly group elicitation?	If yes, will it support decentralized elicitation?	If yes, will it support simultaneous data input?	If yes, does it support simultaneous viewing?	If yes, is a record of model evolution kept?	Capture descriptive comments or narrative during TSE.	Record TSE actions for playback or re-creation of the exploration.	Automatically repopulate the TS based on user-selected seed points.	Create predictive models using multiple techniques (e.g., regression, Kriging, neural nets, etc.).
Definition		Can the user set permissions such that certain model structures or formulae within the tool are protected/hidden from other users?	Does the tool contain separate features or fields for group elicitation (versus single input)?	If the tool explicitly supports group elicitation, does it support decentralized elicitation where multiple users may be geographically separated?	If the tool supports decentralized elicitation from multiple, geographically separated users, does it support simultaneous data input from the users?	If the tool supports simultaneous data input from multiple, distributed users, does it support simultaneous, real-time viewing of the tool canvas or data entry fields?	If the tool supports simultaneous, distributed data input and viewing, does it keep a record of model evolution?	Does the tool allow capture of written/typed or verbal comments during data entry and subsequent viewing of the effect of changing inputs?	Does the tool allow the user to record TSE actions for the purposes of rewinding and playing back (i.e., instant replay) as well as rewinding, playing back, and entering into the process to take a new TSE path?	Can the user "click" within or "point" to a region in the tradespace and set this point as a seed from which the tool can further fill in or re-populate the tradespace?	Can the tool create surrogate models of data such that the data can be replaced with equations?
Tool/Process	**Developer**	51	52	53	54	55	56	57	58	59	60
AAMODAT	RDECOM-ARDEC	N	Y	N	N/A	N/A	N/A	Y	N	N	N
ASEC	RDECOM-TARDEC	N	Y	Y	Y	Y	N	Y	N	N	N
ATSV	Penn State ARL	N/A	Y	N	N/A	N/A	N/A	N	N	Y	N
CPAT	PEO-GCS	?	Y	N	N/A	N/A	N/A	N	N	N	N
Excel	Microsoft	Y	Y	Y	Y	Y	N	Y	Y	N	Y
FACT	GTRI	?	Y	Y	Y	Y	N	Y	N	N	N
JMP	SAS	?	N	N/A	N/A	N/A	N/A	Y	Y	Y	Y
Matlab	Mathworks	?	N	N/A	N/A	N/A	N/A	N	Y	N	Y
ModelCenter	Phoenix Integration	?	N	N/A	N/A	N/A	N/A	N	N	N	Y
OpenMDAO	NASA	N	N	N/A	N/A	N/A	N/A	N	N	N	Y
R	R Foundation	?	N	N/A	N/A	N/A	N/A	N	N	?	Y
TIES	Georgia Institute of Technology	N	N	N	N	N	N	N	N	N	Y
WSTAT	PEO-GCS	N	Y	N	N/A	N/A	N/A	Y	N	N	N

Attribute		Access external databases in real-time to supplement internal data.	Access to cost models, databases, or estimating relationships?	Express alternate use cases and operational scenarios.	Graphical and quantitative assessment of technology readiness, technology maturity, and technology integration levels	Near real-time queries	Customized data layout	Graphical decision network	Selective search	Generate Data Internally	Auto-discover relationships within data
Definition		Can the tool link, or connect, to external databases in order to supplement static data sets within the tool?	Can the tool link to, or plug in to, cost estimating resources?	Can the user generate alternate use cases and operational scenarios to compare to the baseline?	Can the tool graphically and quantitatively express technology readiness, maturity, and integration levels?	Does the tool allow user interaction for scenarios, storylines, and other "what-ifs" that might aid the decision maker and analyst in exploration of impacts due to constraints, assumptions, and technology insertion?	Can the tool create a customized layout of qualitative and quantitative graphics and data?	Does the tool allow for mapping or linking decisions from the high-level decision maker metrics (e.g., cost, schedule) down to the low-level design decisions (e.g., material selection, dimensions/tolerances)?	Can the user execute searches based on user-specified selective dimensions or user-specified regions of the tradespace?	Can the tool internally generate data from models (as opposed to requiring data sets to be imported from other sources which execute models)?	Can the tool automatically discover, identify, or reveal relationships within a dataset or across multiple datasets?
Tool/Process	**Developer**	61	62	63	64	65	66	67	68	69	70
AAMODAT	RDECOM-ARDEC	N	N	N	N	Y	Y	N	N	N	N
ASEC	RDECOM-TARDEC	N	N	Y	Y	Y	N	Y	N	N	N
ATSV	Penn State ARL	N	N	N	Y	Y	Y	N	Y	N	N
CPAT	PEO-GCS	N	N	Y	N	Y	N	N	N	N	N
Excel	Microsoft	Y	Y	Y	Y	Y	Y	N	N	Y	Y
FACT	GTRI	N	N	Y	Y	Y	N	N	N	N	N
JMP	SAS	Y	?	Y	Y	Y	Y	Y	Y	Y	Y
Matlab	Mathworks	Y	?	Y	Y	Y	Y	Y	Y	Y	Y
ModelCenter	Phoenix Integration	Y	?	Y	Y	Y	N	Y	N	Y	Y
OpenMDAO	NASA	Y	Y	N	Y	N	N	N	N	Y	N
R	R Foundation	Y	Y	Y	Y	Y	Y	N	Y	Y	N
TIES	Georgia Institute of Technology	N	N	N	Y	N	N	N	Y	Y	N
WSTAT	PEO-GCS	N	N	N	N	Y	Y	N	N	N	N

				Decision Algorithms Implemented			Availability of graphical elicitation te				
Attribute		Accept real-time user input and steering during the TSE process.	Customize the TSE process, analysis, optimization, or visualization through scripting.	MODA / MAUT	AHP	Other	Model structure / Brainstorming	Value functions / scores	Value weights	Probabilities	Risk preference
Definition		Can the user interject real-time input to the TSE process (i.e., what-ifs from other collaborators)?	Does the tool allow the user to develop their own custom code? For example, multiple JMP analyses can be combined to run in succession within a single JMP script, and VBA can be used to create statistical analyses not available natively in Excel or through add-ins.	Does the tool use any MODA/MAUT algorithms?	Does the tool have built-in capability to perform AHP, including consistency checks?	Does the tool use another decision algorithm other than MODA/MAUT/AHP? If yes, then which ones?	Does the tool use graphical techniques to elicit requirements, ideas, thoughts, or model structure from the user?	Does the tool visually depict value functions to elicit information from the user?	Does the tool visually depict value weights to elicit information from the user?	Does the tool visually depict probabilities to elicit information from the user?	Does the tool visually depict risk preference to elicit information from the user?
Tool/Process	**Developer**	71	72	73	74	75	76	77	78	79	80
AAMODAT	RDECOM-ARDEC	Y	Y	Y	N	N	N	Y	Y	Y	Y
ASEC	RDECOM-TARDEC	Y	N	N	N	N	Y	N	N	N	Y
ATSV	Penn State ARL	Y	N	N	N	N	N	N	N	N	N
CPAT	PEO-GCS	N	N	Y	Y	?	N	Y	Y	N	N
Excel	Microsoft	Y	Y	Y	Y	Any algorithm which can be coded	Y	Y	Y	Y	Y
FACT	GTRI	Y	N	Y	Y	N	Y	Y	Y	Y	Y
JMP	SAS	Y	Y	N	Y	Any algorithm which can be coded	N	N	N	N	N
Matlab	Mathworks	Y	Y	N	N	Any algorithm which can be coded	Y	N	N	N	N
ModelCenter	Phoenix Integration	Y	Y	Y	N	Optimization algorithms	Y	N	N	N	N
OpenMDAO	NASA	Y	Y	N	N	Optimization algorithms	N	N	N	N	N
R	R Foundation	Y	Y	N	N	Any algorithm which can be coded	N	N	N	N	N
TIES	Georgia Institute of Technology	Y	N	N	N	N	N	N	N	N	N
WSTAT	PEO-GCS	Y	Y	Y	N	N	N	Y	Y	Y	Y

		chniques				Types of output displays and analyses charts					
Attribute		Swing weight methods	Can probabilities or weights be defined as variables that can be operated on?	Can the tool generate strategy tables?	Can the user document structure or judgments with text?	Are graphical sensitivity analyses possible on either weights or probabilities?	Can analytical results be portrayed graphically?	Can the tool produce Expected Value (EV) Tornado Diagrams?	Does the software support two-way sensitivity analysis	Does the software determine value of imperfect information?	Select data for plotting and/or analysis through filtering, sorting, selecting, excluding.
Definition		Does the tool implement swing weight methods to graphically elicit information from the user?	Does the tool allow probabilities or weights to be defined as variables?	Does the tool generate strategy tables, where multiple options are listed for multiple decision areas?	Does the tool allow users to document model structure, assumptions, or other judgments with text?	Does the tool plot sensitivity analyses on either weights or probabilities?	Does the tool plot/chart analytical results?	Does the tool produce EV tornado diagrams, such that the user's attention can be called to variables that have the greatest impact on expected value?	Does the tool determine how a combination of any two inputs affects an output?	Does the tool determine value of imperfect information (the amount one would be willing to 'pay' for obtaining additional, uncertain information)?	Can the user select or exclude data from an analysis or plot?
Tool/Process	**Developer**	81	82	83	84	85	86	87	88	89	90
AAMODAT	RDECOM-ARDEC	Y	Y	Y	Y	Y	Y	Y	Y	N	N
ASEC	RDECOM-TARDEC	N	N	Y	Y	N	Y	Y	N	N	N
ATSV	Penn State ARL	N	N	N	N	N	Y	N	N	N	Y
CPAT	PEO-GCS	Y	N	Y	N	N	Y	N	N	N	N
Excel	Microsoft	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
FACT	GTRI	N	Y	Y	Y	Y	Y	Y	Y	N	Y
JMP	SAS	N	Y	Y	Y	Y	Y	Y	Y	N	Y
Matlab	Mathworks	N	Y	N	Y	N	Y	N	Y	N	Y
ModelCenter	Phoenix Integration	N	Y	N	Y	N	Y	N	N	N	Y
OpenMDAO	NASA	N	N	N	N	N	Y	N	N	N	N
R	R Foundation	N	?	?	N	N	N	Y	Y	N	Y
TIES	Georgia Institute of Technology	N	N	N	N	Y	Y	N	N	N	N
WSTAT	PEO-GCS	Y	Y	Y	Y	Y	Y	Y	Y	N	N

Attribute		Visualization of data through linked plots (such as small multiples).
Definition		If multiple plots are laid out on the viewing canvas, can the tool automatically link the plots such that highlighting a point in one plot results in the corresponding points being highlighted in all other plots?
Tool/Process	**Developer**	91
AAMODAT	RDECOM-ARDEC	N
ASEC	RDECOM-TARDEC	N
ATSV	Penn State ARL	Y
CPAT	PEO-GCS	N
Excel	Microsoft	N
FACT	GTRI	Y
JMP	SAS	Y
Matlab	Mathworks	Y
ModelCenter	Phoenix Integration	Y
OpenMDAO	NASA	Y
R	R Foundation	Y
TIES	Georgia Institute of Technology	Y
WSTAT	PEO-GCS	N

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Appendix E. ERS Demonstration Projects

Engineered Resilient Systems (ERS) Demonstration Project 1: Fixed Wing Aircraft seeks to demonstrate "the use of high performance computing and physics-based modeling to rapidly develop a resilient design space during early Analysis of Alternatives of a fixed wing air vehicle."[1] The approach is to link design variables with mission capabilities through physics-based and operational models, respectively. Aircraft design inputs are mapped to operational and cost analysis modeling and simulation (M&S) outputs. The notional steps and corresponding tools used during the project are as follows and as illustrated in Fig. E-1.

1. Consider multiple mission scenarios and keep their requirements open (Tool: not applicable (N/A)—Joint Capabilities Integration and Development System Documents).

2. Execute operational effectiveness models against multiple scenarios and threats (Tool: Analysis of Mobility Platforms [AMP]).

3. Identify set of operational performance metrics and system design variables that impact operational requirements (Tools: DaVinci and AMP).

4. Conduct multidiscipline physics-based analysis of designs. (Tools: DaVinci and Kestrel).

5. Create surrogate response surface models that accurately represent the multiphysics based modeling design tool outputs and inject it into engagement models to show an iterative ability to adjust scenarios and requirements to physical feasibility (Tool: JMP).

6. Perform a structured assessment of cost, schedule, and performance risk using probability based design methods to statistically connect operational requirements and concept feasibility with performance and affordability (Tool: JMP).

[1]Eslinger OJ. Draft engineered resilient systems program management plan. Vicksburg (MS): Army Engineer Research and Development Center (US); 2013.

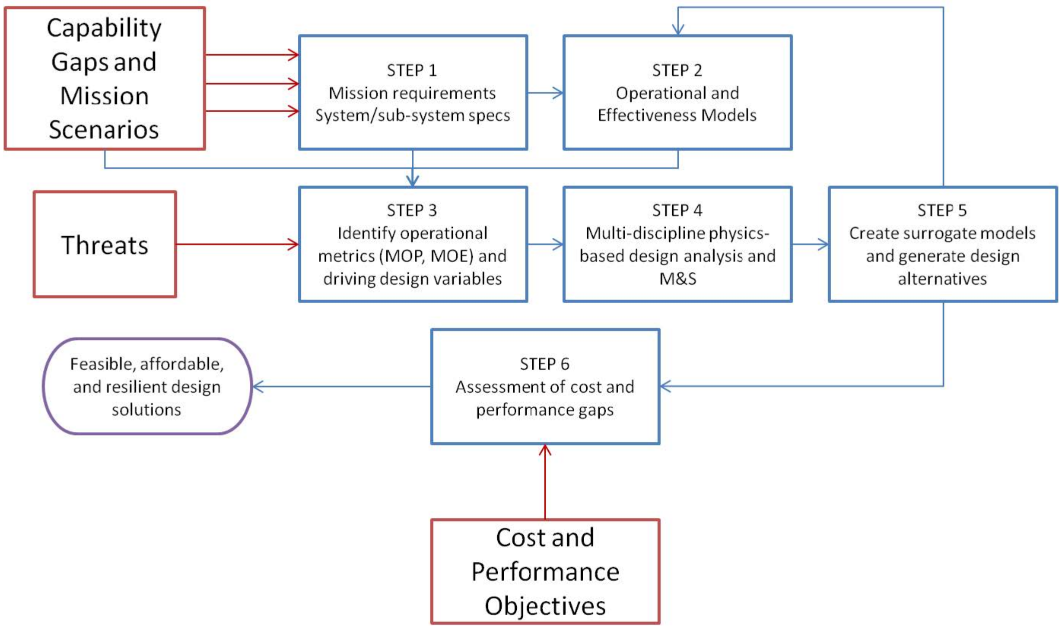

Fig. E-1 TSE steps for DP1

ERS DP2: Ship Design seeks to address the historical point-based design method used by the US Navy through comparison to set-based practice employing physics based modeling and tradespace exploration. In the status quo approach, key design parameters are locked down early to enable continuation into detailed design and manufacturing. However, the design parameter decisions made early in the design process are based on low fidelity information, when the design is immature and uncertainty is high.[1] As the point design process progresses, details emerge about the design and physics-based analysis is conducted, resulting in identification of design deficiencies. To counter these design deficiencies, redesign commences or requirements are relaxed. Continuing, the point design process struggles to keep the ship design feasible given the early decisions that have already locked in key dimensions, and the design is unable to respond to changes. The proposed approach is centered around set-based design, where design variables are parameterized and decisions are postponed until sufficient detail is available. As the sets of designs narrow down, the best solution emerges. Set-based design applied here combines physics-based data with analysis of requirements, concept of operations, measures of effectiveness, technology portfolios, and cost analysis. The notional steps and corresponding tools used during the project are as follows and as illustrated in Fig. E-2.

1. Obtain a baseline ship design (Tool: Advanced Ship and Submarine Evaluation Tool [ASSET], N/A—expert input).

2. Identify set of performance and operational metrics (Tool: ASSET).

3. Synthesize design alternatives and collect output data (Tools: Rapid Ship Design Environment [RSDE], ASSET, Leading Edge Architecture for Prototyping Systems [LEAPS]).

4. Analyze and optimize alternative designs across performance, cost, and risk (Tools: RSDE, ASSET, LEAPS, PBCM, Excel, TIGER, SEAQUEST, ModelCenter).

5. Identify the reduced set of compliant designs based on the bounds applied to design variables and metrics (Tools: RSDE, Excel).

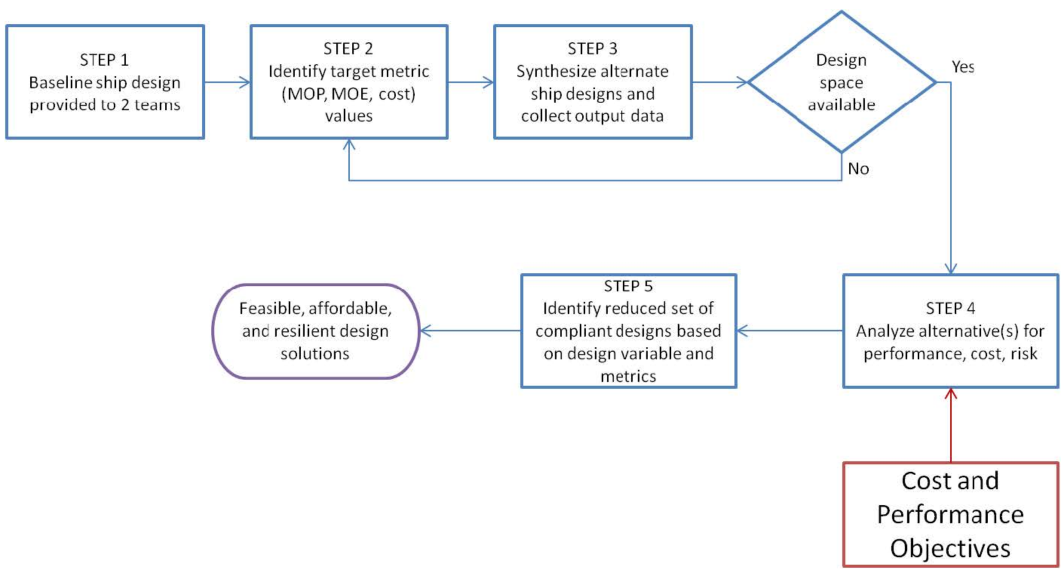

Fig. E-2 TSE steps for DP2

DP3: Sensors Systems DP3 is based on the Geo-Environmental Tactical Simulation program, which is an Army Technology Objective executed by the US Army Engineer Research and Development Center. The objective is to apply "HPC modeling & simulation to improve the detection of buried targets across a number of sensing modes."[1] Targets include improvised explosive devices, explosively formed penetrators, land mines, weapon systems, and caches of various sorts.

The M&S efforts on DP3 seek to understand the full impact of disparate geo-environmental factors (i.e., solar conditions, weather, soil characteristics, vegetation, and natural/man-made clutter) on the performance of electro-optical/infrared and ground-penetrating radar sensor systems.

DP3 will employ virtual reality tools to simulate landscapes, scenes, sensors, and endogenous factors, to infer correlations. The virtual environment will allow multiple users to interact within the scene, choose how to view the data (i.e., via walking, ground vehicles, or air vehicles), and understand how different sensor platforms would perform under various conditions.

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Appendix F. Capability Portfolio Analysis Tool

The Capability Portfolio Analysis Tool (CPAT) was developed to provide a formal, structured process to address the difficulty associated with the decision analysis process within fleet modernization. CPAT follows a value-focused thinking (VFT) approach, which involves decomposing weighted roles into functions and, using a mixed integer linear programming optimization model, develops portfolios of systems that maximize fleet value over time while meeting cost and schedule constraints. The following general steps are conducted within CPAT to conduct tradespace exploration (TSE). An overview description of CPAT is available in Appendix A, in the CPAT section. Outside resources on CPAT are also available.[1–3]

The process within CPAT generally follows the following steps:

1. Gather information
    - Alternative and baseline specifications (system, subsystem, and component level)
    - Mission scenarios and requirements (operational and system level)
    - Measures of effectiveness, measures of performance, key performance parameters, key system attributes, and "ilities"
    - Data and assumptions (schedule, base year, budget available, period of operation)
2. Use expert knowledge (subject matter experts, project managers, and expert knowledge teams) to conduct VFT
    - Break down the mission scenarios and requirements into functional roles
    - Assign values to each role
    - Determine major system attributes that contribute to each value
    - Map measures to each system attribute, and weight their importance using a swing weight matrix

[1]Edwards S, Haas B. Program executive office ground combat systems capability portfolio analysis tool (CPAT). In: Proceedings of the 79th MORS Symposium, WG 27 – Decision Analysis; 2011 Jun 20–23; Monterey, CA. MORSS; 2006.

[2]Ewing L, Dell RF, MacCalman M, Whitney L. Capability portfolio analysis tool (CPAT) verification and validation report. Monterey (CA): Naval Postgraduate School; 2013 Jan. Report No.: NPS-OR-13-001.

[3]Edwards S. Capability portfolio analysis tool (CPAT) & whole system trade analysis (WSTA). Paper presented at: Army Systems Engineering Forum (ASEF). 2013 Feb 27; Arlington, VA.

- Determine value functions; value functions may be dependent on the system performance data (alternatives and baselines specifications)

3. Perform life cycle cost (LCC) estimates of each alternative based on possible courses of action (COAs)

   - Use data and assumptions data when applicable
   - For each alternative, perform a year-by-year LCC estimate
   - Compare the resulting LCC estimates for the different alternatives
   - Based on the comparisons, data, and assumptions, determine feasible COAs

4. Perform a schedule and life cycle analysis

   - Gather research, development, test, and evaluation (RDT&E) and acquisition budget schedule and distribution
   - Determine expected availability date of modernization alternatives
   - Determine the required date for required funds to procure systems
   - Determine dates the alternatives start realizing performance improvements
   - Map the above to life cycle phases (RDT&E, procurement, operation, and retirement)

5. Perform an optimization analysis to determine the optimum alternatives for each COA

   - Gather all requirements and constraints
   - Determine the number of systems for each role (if portfolios are being analyzed)
   - Feed all performance, cost, and schedule data into the CPAT optimization routine and map to objectives and constraints for each COA
   - Formulate the problem as an optimization problem and select the appropriate solver to be used to find the optimum solution
   - Collect optimization results (year-by-year schedule of systems or portfolio alternatives)

6. Perform postoptimization analyses

- Assess the operational impact of the alternatives by looking at how each alternative in each COA meets the roles, and compare the different options
- Perform an industrial base assessment by gathering industrial base data, investment recommendations per role, and minimum sustaining rate, and determine if the alternatives meet the industrial constraints
- Perform a gap analysis by comparing the performance gaps of the current baseline systems or portfolio with the systems or portfolio capabilities of the optimum systems, considering the performance, cost, and schedule

Figure F-1 is a ARL–generated schematic of the CPAT TSE environment, including steps, inputs, outputs, interfaces, and analysis details.

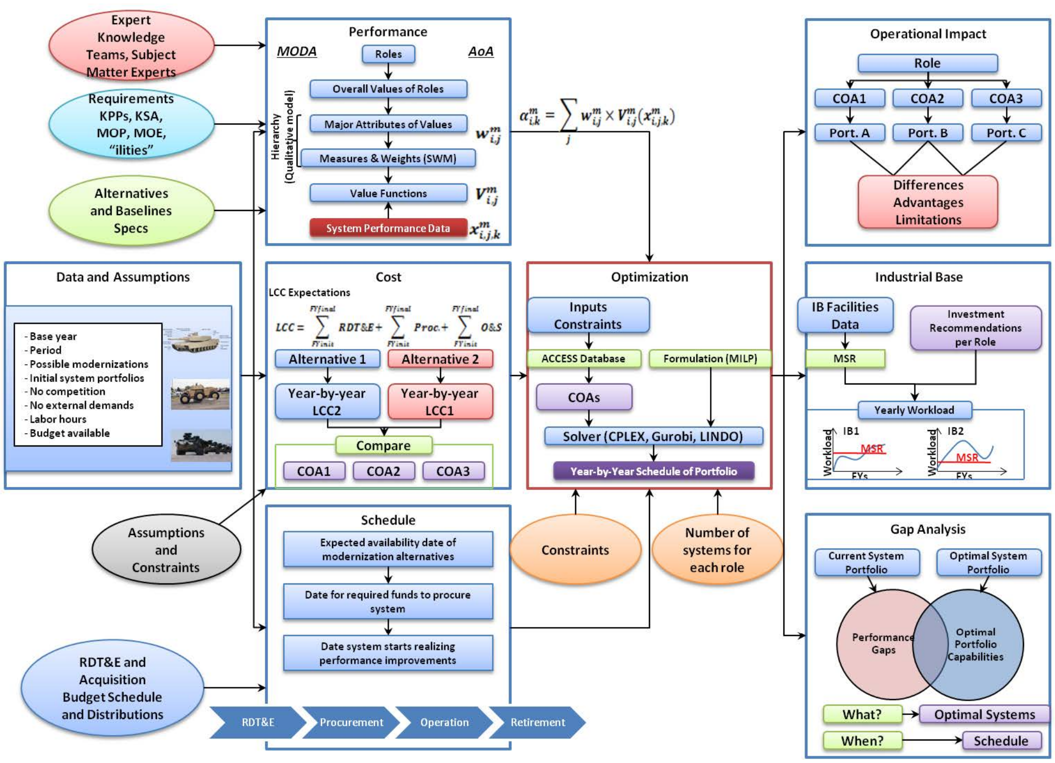

Fig. F-1 CPAT TSE environment

Appendix G. Framework for Assessing Cost and Technology

The Framework for Assessing Cost and Technology (FACT) was developed to provide a formal, structured process for presenting engineering and acquisition decision makers with capability, cost, and performance trades on systems, using the system's physical architecture and quantitative system attributes. FACT was developed as a collaborative environment for conducting model-based systems engineering over the Internet for the purpose of increasing early knowledge of system capability and tradeoffs. An overview description of FACT is available in Appendix A, in the FACT section. Outside resources on FACT are also available. [1,2]

The process within FACT generally follows these steps:

1. Develop or obtain system requirements and translate into systems modeling language (SysML) requirement models
    - Requirements are preserved and updated, while maintaining traceability to verification
2. Define or obtain the system work breakdown structure (WBS) and translate into a SysML block definition diagram
    - The relationships and interfaces within the system hierarchy are maintained and traced
3. Identify alternative subsystems
    - Identify the attributes that define these subsystems and enter quantitative values
    - Map these subsystem attributes to the system requirements
    - Assign qualitative weighting to a subsystem attribute's influence on a system requirement
4. Develop a SysML parametric diagram using parametric blocks
    - Inputs, outputs, constraints, units, and calculations of the parametric blocks are captured in SysML for linking to other blocks

[1] Ender TR, Browne CD, Yates WW, O'Neal M. FACT: an M&S framework for systems engineering. Paper presented at: Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC). 2012 Dec 3–6; Orlando, FL.

[2] Ender TR. Model-based systems engineering as a collaborative web-service. Paper presented at: National Defense Industrial Association Ground Vehicle Systems Engineering and Technology Symposium (NDIA GVSETS). 2013 Aug 20–22; Troy, MI.

- FACT can perform internal calculations using surrogate models, or can call out to externally stored and executed simulations or surrogate models

5. Conduct analysis

    - Configure the system by selecting subsystems to satisfy the necessary WBS level and observe impact on performance requirements
    - Data are exported to the collaborative web server

6. Access graphical user interface and conduct exploration

    - Adjust subsystem performance attributes as necessary to reflect "what-if's"
    - Apply uncertainty to subsystem attributes and run Monte Carlo simulation
    - Multiple users can simultaneously access and view the tradespace environment, making changes to threshold and objectives in real-time as well as filtering data

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List of Symbols, Abbreviations, and Acronyms

AAMODAT	Armament Analysis Multiple Objectives Decision Analysis Tool
AMP	Analysis of Mobility Platforms
ARDEC	US Army Armament Research, Development and Engineering Center
ARL	US Army Research Laboratory
ASDL	Aerospace Systems Design Laboratory
ASEC	Advanced Systems Engineering Capability
ASSET	Advanced Ship and Submarine Evaluation Tool
ATSV	ARL Trade Space Visualizer
CAC	common access card
CART	Classification and Regression Trees
CDF	cumulative distribution function
CFD	Computational Fluid Dynamics
COA	course of action
CPAT	Capability Portfolio Analysis Tool
DAKOTA	Design Analysis toolKit for Optimization and Terascale Applications
DAS	Decision Analysis Software
DOD	Department of Defense
DOE	design of experiments
DP	demonstration project
ERDC	US Army Engineer Research and Development Center
ERS	Engineered Resilient Systems

FACT	Framework for Assessing Cost and Technology
FEA	finite element analysis
FS	functional skeleton
GRIPS	Genetic Resources for Innovation and Problem Solving
GTRI	Georgia Tech Research Institute
GUI	graphical user interface
JIAT	Joint Integrated Analysis Tool
LCC	life cycle cost
LEAPS	Leading Edge Architecture for Prototyping Systems
LMI	Logistics Management Institute
M&S	modeling and simulation
MARS	Multivariate Adaptive Regression Splines
MBSE	model-based systems engineering
MDAO	Multidisciplinary Design Analysis and Optimization
MDO	multidisciplinary optimization
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
N/A	not applicable
O&S	operations and support
OR/MS	Operations Research/Management Sciences
PDF	probability density function
PEO-GCS	Program Executive Office Ground Combat Systems
PSC	Priority Steering Council
PSU-ARL	Pennsylvania State University Applied Research Laboratory

QFD	quality function deployment
RDT&E	research, development, test, and evaluation
RICH	Rank Inclusion in Criteria Hierarchies
ROSETTA	Relational-Oriented Systems Engineering and Technology Tradeoff Analysis
RPM	Robust Portfolio Management
RSDE	Rapid Ship Design Environment
RSE	response surface equation
SAE	Systems Analysis and Experimentation
SAL	Systems Analysis Laboratory
SCAP	System Capabilities Analytic Process
SLAD	ARL Survivability/Lethality Analysis Directorate
SPIDR	Systems Platform for Integrated Design in Realtime
SUF	single utility function
SysML	systems modeling language
TARDEC	US Army Tank Automotive Research, Development and Engineering Center
TIES	Technology Identification, Evaluation, and Selection
TRACER	Tradespace Analysis for Capabilities, Effectiveness, and Resources
TSE	tradespace exploration
VBA	Visual Basic for Applications
VFT	value-focused thinking
VisualDOC	Visual Design & Optimization Control
VTD	Vehicle Technology Directorate

WBS	work breakdown structure
WSTAT	Whole System Trades Analysis Tool

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
2 (PDF)	DIRECTOR US ARMY RESEARCH LAB RDRL CIO LL IMAL HRA MAIL & RECORDS MGMT
1 (PDF)	GOVT PRINTG OFC A MALHOTRA
2 (PDF)	GEORGIA INST TECHNOLOGY DEPT AERO ENG D MAVRIS P VALDEZ
1 (PDF)	US ARMY ERDC RDE-ITL-MS S GOERGER

ABERDEEN PROVING GROUND

4 (PDF)	DIR USARL RDRL VTS H RUSSELL RDRL VTV M AVERA E RIGAS E SPERO

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